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RESEARCH MEMORANDUM

DESIGN OF APPARATUS FOR DETERMINING HEAT TRANSFER AND FRICTIONAL PRESSURE DROP OF NITRIC ACID FLOWING THROUGH A HEATED TUBE

By Bruce A. Reese and Robert W. Graham

Purdue University

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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SUMMARY

The object of the research project described herein is to present the design basis for test apparatus to determine the heat-transfer and pressure-drop characteristics of white fuming nitric acid flowing in a heated tube section. The heat flux to the tube will be of the order of magnitude occurring in a regeneratively cooled rocket engine.

INTRODUCTION

Adequate cooling of a liquid-propellant rocket engine is one of the most challenging problems to be solved if higher-energy propellants or higher combustion pressures are to be utilized. Currently liquid-propellant rocket engines employ "regenerative cooling." One of the propellants in its passage to the injection system is circulated around the thrust chamber, as a coolant, before it is injected therein.

The mechanics of the heat transfer with regenerative cooling can take place in two different ways:

(a) The heat is transferred from the hot metal wall to the flowing liquid propellant which always remains in the liquid phase, the heat transfer being accomplished principally by forced convection.

(b) The liquid does not remain entirely in the liquid phase. Vaporization or boiling takes place along the metal surfaces, the vapor being carried away by the cooler liquid. It is known that there are two different types of boiling which may occur depending upon the magnitude of the heat flux. As a liquid is heated by a metal surface, the first type of boiling to occur is "nucleate boiling." Vapor bubbles are formed at the metal surface and are absorbed by the cooler liquid. If the heat flux is increased the vapor bubbles increase in size until a continuous vapor layer forms immediately adjacent to the metal wall, and what is termed "film boiling" takes place. The vapor layer increases the resistance to heat flow thereby promoting the danger of burnout. Although much information has been compiled on allied heat-transfer data (references 1 to 19), the rocket motor designer needs specific data which will enable him to predict accurately the heat-transfer characteristics of the liquid propellants to be employed as coolants so that his designs will preclude the occurrence of vapor-film boiling.

White fuming nitric acid (abbreviated hereafter as WFNA) is currently specified as the oxidizing agent for several liquid-propellant rocket developments. Consequently, there is interest in securing data on its heat-transfer properties under conditions comparable with those encountered in rocket engines regeneratively cooled with WFNA.

This report presents the design basis for the test apparatus which is being constructed for measuring the heat-transfer and pressure-drop characteristics of WFNA under conditions simulating those for a WFNA regeneratively cooled rocket engine. The apparatus is designed so that heat-transfer and fluid-friction data can be obtained over the following ranges:

(a) Inlet pressure to test section, atmospheric to 400 pounds per square inch absolute

(b) Mean fluid temperature at entrance to heated test section, -30° to 300° F

(c) Heat input to test section, 0.5 to 1.5 Btu per second per square inch and as far above as possible

(d) Reynolds number, 60,000 to 200,000 and as far above as possible

The apparatus is being erected in the Purdue Research Laboratory under the sponsorship and with the financial assistance of the National Advisory Committee for Aeronautics.

Acknowledgment is due Dr. M. J. Zucrow, project director, for his suggestions during the design of the equipment and for his help in the preparation of this report. Appreciation is expressed for the continuous assistance of Dr. C. F. Warner and to Mr. D. W. Craft who did much of the electrical design of the apparatus while employed by the project during its initial period. We would also like to express our gratitude for the wholehearted cooperation we have received from the NACA staff of the Lewis Flight Propulsion Laboratory, Cleveland, Ohio.

GENERAL ARRANGEMENT OF APPARATUS

Figure 1 illustrates schematically the general arrangement of the apparatus, which comprises the following main components:

(a) Acid flow circuit

(b) Electrically heated test section

(c) Instrumentation

A perspective view of the apparatus before installation of the acid pump is shown in figure 2.

Acid Flow Circuit

Selection of materials.- Because of the extremely corrosive nature of WFNA careful study was given to the selection of the materials that are to come in contact with the acid. The materials recommended by the "Corrosion Handbook" (reference 10) are presented in table I for reference.

Of the materials in table I those possessing better corrosion resistance at elevated temperatures are : IA, IB, IC, IE, IF, 3A, 3B, 8C, 8D, 20A, 20B, 20C, 22A, 22B, and 22C.

Experiments conducted under the direction of Dr. W. L. Sibbitt, Purdue University, indicate that H.S. 25 alloy (L605) produced by Haynes Stellite Company should be added to the materials listed in table I. Its corrosion resistance to WFNA at elevated temperatures exceeds that of 2S aluminum, which is considered to be one of the better acid-resistant alloys.

In the selection of materials for the heat-transfer apparatus corrosion resistance was considered the most important property, but such secondary considerations as strength and cost eliminated such acid-resistant materials as glass, porcelain, chemical stoneware, the high-silicon cast irons, and the noble metals. Cost and strength considerations eliminated all of the corrosion-resistant materials except the stainless steels, aluminum, and H.S. 25. Of these three materials H.S. 25 appears to have the best corrosion resistance but is more costly and more difficult to weld, machine, bend, and so forth than the stainless steels or aluminum. Consequently, H.S. 25 was selected only for those places in the circuit where it could not be adequately replaced by the more easily worked stainless steels or aluminum.

Since the corrosion resistances of the stainless steels are similar, it was decided to use, wherever possible, AISI Types 316 and 347. These steels can be welded (without subsequent annealing) without danger of carbide precipitation with its attendant intergranular corrosion. Fittings, tubing, piping, and valves are available in Types 316 and 347, the latter being preferred because it possesses slightly better resistance to corrosion by nitric acid and is easier to weld.[1]

The materials for the following components have been specified to be stainless steel: Acid pump, Type L-20 (manufacturer's designation); piping, Type 347; threaded valves, Type 316; threaded valves, Type 304; flanges, Type 347; pipe fittings, Type 316; tubing for instrumentation, Type 304; and acid tanks, Type 347.

The alloy H.S. 25 will be used for the test section and the upstream and downstream mixing chambers.

The double-pipe heat exchanger is to be fabricated from aluminum tubing. Aluminum was selected for the application because of its high thermal conductivity, good corrosion resistance, and the ease with which it can be worked and welded. Type 3S-H14 Alcoa aluminum is to be used for the 1-inch-outer-diameter tubing which will be in contact with the WFNA and Type 61S, for the outer $1\frac{1}{2}$-inch-outer-diameter tubing because 3S-H14 was not available in that size.

Where two dissimilar metal parts are connected, care must be exercised to insulate them from each other electrically. Dissimilar metals in contact in an electrolyte, such as nitric acid, behave as a galvanic cell and cause galvanic corrosion. It has been pointed out that galvanic corrosion probably cannot be eliminated by insulating between the dissimilar metals in the test apparatus, because of the possibility of transfer of metal particles through the acid.[2] It is believed, however, that the cost and fabrication advantages of using the three different types of metals will more than compensate for the replacement of the parts which may become damaged by galvanic corrosion.

Arrangement of acid flow circuit.- The acid flow circuit is designed so that the desired range of flows and temperatures can be obtained at the inlet to the electrically heated test section. The required weight and volume flows of WFNA to cover the desired range of Reynolds numbers and inlet temperatures to the test section (I.D., 0.539 in.) are presented in figures 3 and 4, respectively. Figure 3 presents the weight

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[1]Information obtained from "Allegheny Stainless Steel Data Book" (reference 11).

[2]Private communication.

flow rate as a function of inlet temperature for two different Reynolds numbers, $R_e = 60{,}000$ and $R_e = 200{,}000$, which are the minimum and maximum, respectively, to be investigated. Figure 4 presents the corresponding volumetric flow rates. In making the calculations for figures 3 and 4 published data on the physical properties were used, and those data are of questionable accuracy.[3] The curves are, however, sufficiently accurate for apparatus design purposes.

Employing the volume flow calculations (see fig. 4) as a basis the system was designed for a maximum WFNA flow of 30 gallons per minute. It should be noted that a flow of 30 gallons per minute is insufficient to produce a Reynolds number of 200,000 (proposed maximum) at low inlet temperatures. However, it is believed that the decision to design for a flow of 30 gallons per minute was a reasonable compromise between apparatus cost and the desired information; the major portion of the desired flow rates and the majority of the data can be obtained with flows considerably smaller than 30 gallons per minute.

As shown in figure 1, the acid is supplied to the test section h by the pump a which develops sufficient head to overcome the resistance of the circuit. A portion of the acid leaving the pump may be bypassed, through valve b, to obtain the desired pump operating conditions. By adjustment of the bypass valve b and the throttle valve c the desired head and flow quantity can be obtained. Before entering the test section the WFNA is metered by a calibrated flat-plate orifice d designed as nearly as possible in accordance with the A.S.M.E. flow measurement code.[4] A small 7-gallon tank e is installed upstream of the test section to eliminate any surge and also to provide a means of pressurizing the acid circuit; the acid circuit is pressurized with nitrogen gas from nitrogen cylinders controlled by a Grove regulator. The two Annin valves f and j on the upstream and downstream sides of the test section are installed for safety purposes. The valve controls are designed to close the valves rapidly in case of a test-section failure. The Annin valves should prevent large quantities of acid from spraying the apparatus and causing corrosion damage in the event the test section burns out.

Mixing chambers g and i are installed upstream and downstream of the test section. They are designed to mix the acid thoroughly so that the bulk (mixing cup) temperature can be measured accurately. To insure a uniform velocity profile for the WFNA entering the test section, a

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[3]Physical properties of WFNA are currently being measured at Purdue University, under NACA sponsorship and should be completed by the time they are needed to correlate the experimental data obtained from the investigation of the heat-transfer and fluid-friction characteristics of WFNA.

[4]See reference 18 for A.S.M.E. code.

length of tube equal to approximately 30 tube diameters is inserted between mixing chamber g and the test section.

The test section h is a 5/8-inch-outer-diameter tube 24 inches long, and is heated electrically. Pressure-drop and surface-temperature measurements will be made on the test section h to obtain the friction and heat-transfer coefficients. The heat added to the WFNA in flowing through the test section is removed in the heat exchanger k so that equilibrium conditions may be established.[5] Valves m, n, and p are provided at the exit from the heat exchanger for draining and flushing the system. Provisions have been incorporated for purging the acid flow system with air or nitrogen and for flushing it with water. The acid flow system is filled initially from the large storage tank q; the storage tank is pressurized by nitrogen and the circuit valves b, c, f, j, and n and the vent on the small acid tank e are opened. The acid in the flow system can be returned to tank q before purging the system.

The components briefly mentioned above are discussed in more detail below.

Acid pump (a): An effort was made to secure a pump fabricated from H.S. 25 because of the good corrosion resistance of that alloy to nitric acid. Ampco Metal, Inc., offered to investigate the possibility of constructing a pump of H.S. 25, and the Haynes Stellite Company agreed to cast and machine such parts as the casing, impeller, and so forth. However, Ampco Metal, Inc., could not obtain a satisfactory mechanical seal for the pump; they contended that a pump operating under the severe conditions specified should be equipped with a mechanical seal. Because of the lack of an adequate mechanical seal Ampco Metal, Inc., withdrew their offer to build the pump. Considerable effort and time had been expended on the pump problem so in order to avoid further delay it was decided to purchase a stainless-steel pump manufactured by the Lawrence Machine and Pump Corporation. The pump is designed to supply 30 gallons per minute with a pressure increase of 100 pounds per square inch and to withstand a pressure of 600 pounds per square inch absolute. All parts coming in contact with the acid are to be made of L-20 stainless steel (manufacturer's designation). The packing box and bearings are to be water-cooled, and it is driven by a 60-cycle, three-phase, 220-volt motor.

Bypass system (b): The bypass system is constructed of 3/4-inch pipe of Type 347 stainless steel with an Annin Annico Throttler valve

[5]Vapor-pressure studies of WFNA at Purdue University indicate that at temperatures above approximately 120° F, decomposition of WFNA is so great that it may be necessary to bypass the heat exchanger and to discard the acid.

constructed entirely of Type 316 stainless steel. As pointed out above, the bypass system is to be used for returning a portion of the acid discharged from the pump to the suction side of the pump without passing through the test section.

Throttle valve (c): The throttle valve c is to be used in conjunction with the bypass system to regulate the acid flow to the test section. The valve is a 3/4-inch Annin Domotor valve constructed entirely of Type 316 stainless steel. It is a pneumatically operated valve in which the basic element is a combination "O" ring sealed cylinder and piston. The piston is loaded with air at 25 pounds per square inch absolute from the air supply of 175 pounds per square inch available at the Purdue Rocket Laboratory, by means of a combination air filter, pressure reducing, and back-pressure regulator. The air for controlling the valve position is supplied by a 1/4-inch Annin Model 40-30 Remote Control Valve which reduces the pressure of the main air supply (175 lb/sq in.) to the actuating air-supply pressure (between 3 and 15 lb/sq in.). With the above arrangement it is possible to control the valve position to the nearest 0.001 of an inch anywhere in the piston stroke. The valve body is constructed to give smooth, nonturbulent flow characteristics with an internal flow area equal to that of the 3/4-inch pipe.

Flat-plate orifice (d): An A.S.M.E. type flat orifice is incorporated in the acid circuit approximately 60 pipe diameters downstream from the throttle valve. The A.S.M.E. code cannot be followed because the minimum pipe size permitted by the code is 1 inch and the acid circuit pipe size is 3/4 inch. However, the method and recommendations of the code were followed as closely as possible in the design of the orifice flanges and orifice plates. A Statham differential-pressure transducer measures the pressure differential created by the orifice plate. A more complete description of the differential-pressure measurement is presented in the section "Flow rate of acid." The Statham gage has a range of 0 to 25 pounds per square inch absolute and in order to cover the desired range of flows it has been necessary to construct three orifice plates, each covering a portion of the total range. These orifice-plate calculations are presented in appendix A. The design of the orifice meter, incorporating radius taps, are illustrated in figure 5. The orifice plates will be calibrated in position.

Small acid tank and acid circuit pressurization (e): A 7-gallon acid tank, taken from an Aerojet Model 25 ALDW 1000 liquid Jato unit, is incorporated in the acid flow system to reduce the fluctuations in the weight flow and to furnish a convenient place for pressurizing the system. The tank is spherical and is constructed of Type 347 stainless steel.

The pressure at the entrance to the test section is to be varied from a minimum pressure of about 25 pounds per square inch absolute, the pressure head necessary for circulating the acid, to a maximum of 400 pounds per square inch absolute. The acid circuit is to be pressurized with nitrogen gas, the pressure being regulated by a Grove high-pressure regulator, small-volume, Model 15SW. Two regulators were purchased to cover the required range of pressures, one with a range from 50 to 300 pounds per square inch and the other with a range from 150 to 750 pounds per square inch.

Safety valves (f and j): After investigating a number of quick-closing valves for preventing the escape of the acid in the event of test-section burnout it was decided to incorporate standard Annin Domotor control valves. In the quick closure application of the Domotor valve, an air supply of 30 pounds per square inch from a 1/4-inch combination pressure-reducing and back-pressure regulator valve is piped directly through a 1/4-inch Crescent four-way solenoid valve to the lower side of the piston of both Domotor valves. In case of test-section failure, a relay operates the solenoid valve which exhausts the air from under the piston. Immediately the loading pressure acting on the top of the piston moves the piston downward, closing the Annin valve.

Mixing chambers (g and i): Figures 6 and 7 illustrate the design features of the upstream and downstream mixing chambers. A photograph showing the mixing chambers and the safety valves is given in figure 8. The chambers are designed to mix the acid thoroughly to reduce any nonuniformity in the temperature of the acid. The positions where the bulk temperature of the acid is measured are indicated in the figures. During the calibration runs a traverse across the cross section was conducted for establishing the effectiveness of the mixing and the optimum location for measuring the bulk temperature.

In the upstream mixing chamber a section of tube $16\frac{1}{2}$ inches long (equal to approximately 30 diam) is incorporated to insure fully developed turbulent flow at the entrance to the test section. The above length of upstream tube is necessary to establish the turbulent flow.

Static pressure taps are incorporated in the 1/2-inch ASA flange of the upstream and downstream chambers. These taps connect to annular rings formed by cutting the internal diameter of the gasket (which is between the mixing chamber and test-section flanges) 1/16-inch larger than the internal diameter of the tube. The inlet pressure to the test section will be measured with a stainless-steel Bourdon tube gage.

Test section (h): Tubing made of H.S. 25 was selected for the test section because of its good resistance to corrosion by WFNA. The nearest size available to the proposed tube of 0.500-inch internal diameter was tubing of 5/8-inch external diameter; the latter has an internal diameter of 0.539 inch. The tube is 24 inches long and is to be equipped with Van Stone flanges at each end. The ring holding the Van Stone flange will be constructed of H.S. 25 and welded to the tube. The flanges will be made from 3/4-inch, electrolytic, tough-pitch copper placed to match 1/2-inch, 600-pound ASA flanges. The copper flanges will be connected to the bus bars from the transformer and will conduct the electric current to the tube. The surface temperature of the tube will be measured at several positions by thermocouples, and the pressure drop in the tube will be measured by a Statham transducer. The location of the thermocouples and pressure pickups and the methods of measurement are discussed in the sections "Measurement of frictional pressure drop across test section" and "Measurement of surface temperature of test section." To reduce the heat loss from the tube, the tube and mixing chambers will be insulated with glass wool.

Heat exchanger (k): To establish equilibrium in the acid circuit when operated as a recirculating system the heat added in the test section is to be removed in a heat exchanger. The calculations for the exchanger are presented in appendix B. A sketch of the exchanger is presented in figure 9 and a photograph is shown in figure 10. The exchanger is of the double-pipe type, consisting of six 8-foot lengths of 1-inch 3S-H14 aluminum tubing inside $1\frac{1}{2}$-inch 61S aluminum tubing. The exchanger is designed to give a high coefficient of heat transfer on the water side so that the tube temperature will be close to the water temperature. By keeping the tube temperature low the corrosion rate will be reduced.

The apparatus for supplying the cooling medium to cool the acid is being constructed as a separate system, having its own storage, pump, and piping. With that arrangement it will be possible to use refrigerants for producing low acid temperatures. Water will be the coolant for all tests where the WFNA enters the test section at temperatures above 100° F.[6] The water will be stored in a 1000-gallon tank from which it will be pumped by a two-stage Worthington centrifugal pump; the latter has a capacity of 100 gallons per minute at 139 pounds per square inch. An orifice plate in conjunction with a Tube Turns orifice flange for $1\frac{1}{4}$-inch pipe is to be used for measuring the water flow rate. The differential pressure across the orifice plate will be read on a reservoir-type mercury manometer. The water flow will be divided before entering the heat exchanger. To avoid excessive pressure drop

[6]Recent information indicates that at high acid inlet temperatures it may be necessary to discard the acid and not recirculate it. Provisions for accomplishing this are being studied.

on the water side of the heat exchanger and still maintain the required heat-transfer coefficient it is necessary to divide the flow. At the most severe condition for cooling the acid with water, 50 gallons per minute will be circulated through the top three tubes and 50 gallons per minute, through the lower three tubes. At other conditions the water flow will be divided so the most rapid cooling of the acid is achieved.

After passing through the exchanger the water is returned to the tank. Using a tank for water storage makes it possible to soften the water to reduce the formation of scale on the tubes.

Valves (m, n, and p) for draining and flushing acid flow system: The shut-off valve in the acid in the acid circuit (valve n) is a 3/4-inch Annin Throttler valve constructed of Type 316 stainless steel. The drain and flush valves (m and p) are 3/4-inch Edward threaded valves of Type 304 stainless steel.

The system is drained by opening valve m. The acid circuit may be flushed with air or water by opening the appropriate valve. After the flusing medium has been selected flushing is achieved by closing valve n and opening valve p.

Storage tank (q): The acid is to be stored in a stainless-steel tank removed from an Aerojet Model 38 ALDW 1500 liquid Jato unit. The tank is spherical and constructed entirely of Type 347 stainless steel. The acid stored in the tank is forced into the acid flow circuit by means of nitrogen pressure. After the acid circuit has been filled the valve in the line leading from the tank is closed and the nitrogen pressure is removed from the tank. If at the completion of a test period it is desired to save the acid it can be drained back into the acid storage tank; the acid circuit is designed so that the acid storage tank is the lowest point in the circuit.

Electrical Heating of Test Section

Electrical resistance heating of the test section was preferred to the other methods of heating because it offers the advantages of accurate control and ease of measurement of the electrical power consumption.

Several proposals for supplying a high-amperage, low-voltage, single-phase current were studied. The one which was deemed most feasible and has been installed consists of: (1) A motor-generator set which converts the available three-phase power to single-phase power and (2) a multiple-tap step-down transformer which converts the power from the generator into a high-amperage, low-voltage power supply for the purpose of heating the test-section tube.

A schematic diagram of the electrical system for heating the test section is presented in figure 11. The single-phase motor-generator set is rated at 120 kilovolt-amperes. It was originally a 187-kilovolt-ampere three-phase generator in which the windings were regrouped to produce single-phase current. The supplier of this piece of apparatus designed the newly modified windings so that the current unbalance in the windings is at a minimum and consequently the objectionable unbalance heating effects are minimized. A variable resistance is incorporated in the generator field exciter circuit which allows regulation of the generator output within a range from approximately 120 to 240 volts. Consequently, the combination of the exciter control and the multitap transformer makes available a wide range of supply voltages for heating the test section.

The transformer is a 24:1 single-phase power transformer that incorporates tap switches and taps to permit changing the output voltage and current. When the input to the transformer is 240 volts the output can be varied through a range of from 10 to 40 volts with 39 increments of voltage within the range. By controlling the field excitation of the single-phase generator the output voltage can be reduced to approximately 5 volts. The maximum current output from the transformer is 2500 amperes.

Heavy copper bus bars and connectors will carry the current from the the transformer to the H.S. 25 alloy test section.

The power supplied to the test section will be measured with a wattmeter. The high current through the bus bars prohibits connecting a wattmeter directly to the bus bars; consequently a current transformer will be inserted between the bus bars and the wattmeter. Appendix C presents a method of calculating the heat-flux density to the test section.

Instrumentation

The following variables are to be measured during the experiments:

(1) Flow rate of the acid

(2) Frictional pressure loss in the test section

(3) Surface temperature of the test section

(4) Bulk temperature of the acid entering and leaving the test section

(5) Flow rate of cooling water to the heat exchanger

The following paragraphs describe the instrumentation for measuring the variables mentioned on the preceding page.

Flow rate of acid.- The thin-plate orifice was selected as the acid flowmeter. Since it will be calibrated in place, the principal instrumentation problem is that concerned with the accurate measurement of the pressure differential across the orifice plate. The differential-pressure meter must be capable of withstanding high pressures as well as the corrosive action of the WFNA. Based upon experience, the application of seal pots to isolate the acid from the meter was eliminated from consideration. A Statham Model P-63 differential-pressure transducer was selected for measuring the differential pressure; the output of the Statham transducer will be indicated on a hand-balanced potentiometer. A photograph showing the acid flow meter and the Statham transducer is given in figure 12. Appendix D presents further details on the method of acid flow measurement.

Measurement of frictional pressure drop across test section.- The pressure drop of the WFNA flowing through the test section will be measured as a function of flow rate for different heat inputs and Reynolds numbers. The upstream and downstream flanges of the test section are equipped with piezometer taps for making the pressure-drop measurements. The two pressure taps will be connected to a Statham differential-pressure transducer and the electrical output of the transducer will be measured by a manually balanced potentiometer. Figure 13 is a wiring diagram of the electrical circuit for the measurement of the frictional pressure drop. The relationship between the poteniometer reading and the pressure drop has been calculated and is presented in appendix E.

Measurement of surface temperature of test section.- Eighteen thermocouple stations will be installed for measuring the temperatures along the exterior surface of the heated test section. The thermocouples will be located approximately 3 inches apart and arranged in two banks that are 180° apart. The thermocouples are to be of 30-gage Chromel-Alumel wire and will be welded to the exterior surface of the tube. The temperatures will be recorded directly on an electronic self-balancing Brown potentiometer. The hand-balanced potentiometer mentioned in the preceding section will be used for calibrating the system comprising the thermocouples and the Brown recorder. Calibrations of Brown potentiometers indicate that their readings are sufficiently accurate for the measurement of the surface temperature of the test section.

Measurement of bulk temperature of acid entering and leaving test section.- The acid temperature entering and leaving the heated test section will be measured with Chromel-Alumel thermocouples inserted in the mixing chambers (g and i of fig. 1). To protect the thermocouple wires from the corrosive action of the WFNA, they will be enclosed in stainless-steel tubing.

The temperature of the WFNA measured in the upstream mixing chamber will be taken as the temperature of the acid entering the flowmeter orifice plate, and that temperature will be used for calculating the density of WFNA in computing the mass flow of WFNA. It was decided that the mixing-chamber temperature should be more accurate than the temperature obtained by a thermocouple located just downstream from the orifice plate.

Flow rate of cooling water.- The measurement of the flow of cooling water through the heat exchanger is considered to be of secondary importance. The principal reason for making this flow measurement is for guidance in controlling the cooling of the WFNA as it passes through the heat exchanger. A thin-plate orifice is to be employed for measuring the cooling-water flow. The differential pressure created by the orifice will be measured by means of a 60-inch reservoir-type mercury manometer. One orifice plate will be sufficient for the entire range of water flow rates.

Safety devices.- The safe operation of the apparatus requires several protective devices. Three principal types of mishaps could occur which could damage the test equipment seriously and possibly create a hazard to the operating personnel. They are:

(a) Blockage of the tube test section by foreign matter

(b) Structural failure of the test section

(c) Burnout of the test section

To minimize the dangers which might be created by the failures outlined above, the following electrical safety controls have been incorporated into the apparatus:

(1) The electrical output from the differential-pressure transducer that indicates the pressure drop across the test section is connected to a Sensitrol unit. When an excessive pressure drop occurs across the test section the Sensitrol unit will be adjusted to trigger a relay circuit that will shut down the acid pump, the electrical heating system, and close the two Annin safety valves. The object of the above safety system is to shut down the complete apparatus should the test section become blocked or fail structurally.

(2) During a test run at high heat-flux density there is the possibility of the acid flow being insufficient to cool the test section adequately. To guard against damage from such an occurrence, a relay is installed which will shut down the electrical-heating input before a burnout of the test section occurs. The relay circuit consists of a Sensitrol unit connected to a pair of the thermocouples located on the

test section. When a predetermined temperature is reached, the Sensitrol energizes a relay which in turn cuts off the electrical power supply. It is estimated that the maximum allowable tube surface temperature is approximately 700° F and in the initial runs the Sensitrol will be set to trip the relay at that temperature. After a series of preliminary runs have been made, it may be found that higher tube temperatures can be tolerated, in which case the Sensitrol will be adjusted to trip at a higher temperature. More detailed information regarding the relays for the safety controls is presented in appendixes F and G.

The test cell in which the apparatus is being erected has been designed to provide the maximum safety to the operating personnel. The cell that houses the test apparatus is isolated from the control room by means of a masonry wall. The test cell is equipped with a water flushing system so that if a serious acid leak occurs the cell and equipment can be flushed.

Purdue University
Lafayette, Ind., June 15, 1951

APPENDIX A

DESIGN OF ORIFICE FOR MEASURING ACID FLOW RATE

The acid flow rate is one of the most important measurements to be made in the determination of the fluid-friction and heat-transfer characteristics of WFNA. Because the orifice-plate type of flowmeter is reliable and simple, it has been selected for the primary measuring device. The differential pressure produced by the orifice plate will be measured by a Statham transducer.

Since the A.S.M.E. power test code gives flow coefficients only for the following range - pipe size, 2 inches $< D_1 <$ 24 inches; throat diameter, $D_2 > 3/8$ inches; diameter ratio, $0.15 < (D_2/D_1) < 0.75$ - it was not possible to follow the code completely in designing a square-plate orifice for the 3/4-inch pipe. The recommendations of the code regarding pressure tap hole, size, diameter ratio, and plate thickness, however, were followed whenever possible.

This appendix presents the method used to calculate the size of the holes in the orifice plate.

The basic equation used for the calculations is

$$G = 0.668A_2KE\sqrt{\gamma\ \Delta p}$$

where

G weight rate of flow, lb/sec

A_2 area of hole, sq in.

K coefficient of discharge with approach factor included

E coefficient to correct for dimension change due to temperature

γ specific weight, lb/cu ft

Δp differential pressure across orifice, lb/sq in.

For an orifice plate the flow coefficient K is empirical and includes corrections for friction, for the vena contracta, for the velocity profile, and for the approach velocity. In geometrically similar installations of orifice plates, it is known that the flow coefficient depends on the Reynolds number, the roughness ratio, and the Mach ratio. The Mach ratio is believed to be of secondary importance. As the Reynolds number is increased the flow coefficient will gradually approach a value that is nearly constant. It appears from the figures in the A.S.M.E. test code that for the range of pipe sizes from 2 to 16 inches the flow coefficient is practically independent of pipe size.

Of the three methods of locating pipe taps for measuring the differential pressure (flange taps, radius taps, and vena-contracta taps) the most suitable for variable flows in small pipe sizes is the radius tap. The flow coefficients for radius taps in a 2-inch pipe were used in the calculations.

To achieve adequate accuracy of the differential-pressure-drop measurement over the entire flow range it is necessary to use three orifice plates. The flow varies from a minimum of 0.392 pound per second at 300° F to a maximum of 7.1 pounds per second at 0° F. The three orifice-plate throat diameters and approximate weight-flow ranges are given below:

Throat diameter	Weight-flow range (lb/sec)
5/16 drill (0.312 in.)	0.4 to 1.5
29/64 drill (0.453 in.)	1.4 to 3.2
37/64 drill (0.5781 in.)	3.0 to 7.1

A sample calculation for the throat diameter follows.

Given information:

Weight flow, lb/sec 0.392
Acid temperature, °F 300
Desired differential pressure, lb/sq in. 2

Calculation:

$$A_2 = \frac{G}{0.668KE\sqrt{\gamma\ \Delta p}}$$

Assume $K = 0.65$ and

$$A_2 = \frac{0.392}{0.668 \times 0.65 \times 1.002\sqrt{79.6 \times 2}}$$

$$= 0.0716 \text{ sq in.}$$

$$D_2 = 0.302 \text{ in.}$$

A standard drill size of 5/16 inch (0.312 in.) is therefore selected which gives an area $A_2 = 0.0765$. The actual flow coefficient is established by the Reynolds number and the ratio of the throat diameter to the upstream-pipe internal diameter D_2/D_1.

$$R_d = \frac{48G}{\pi D_2 \mu_2}$$

μ_2 absolute viscosity, lb/ft-sec

G weight flow, lb/sec

D_2 throat diameter, in.

$$R_d = \frac{48 \times 0.392}{\pi \times 0.312 \times 0.000215} = 89,300$$

$$D_2/D_1 = 0.312/0.824 = 0.379$$

From figure 36(a) of the A.S.M.E. test code, $K = 0.61$.

A calculation is made to determine if the throat diameter selected (0.312 in.) gives the desired differential pressure (2 lb/sq in.).

$$\sqrt{\gamma\ \Delta p} = \frac{G}{0.668 A_2 KE}$$

$$= \frac{0.392}{0.668 \times 0.0765 \times 0.61 \times 1.002}$$

$$= 12.55$$

$$\Delta p = \frac{12.55^2}{79.6} = 1.98 \text{ lb/sq in.}$$

APPENDIX B

HEAT EXCHANGER

Thermal equilibrium is established in the acid circuit by removing, in a heat exchanger, the amount of heat added to the acid in the test section. This appendix presents the method used for design calculations for the heat exchanger.

Analyses of the tube and shell type of heat exchanger indicate that with the low coolant velocities characteristic of this type of exchanger the tube metal temperature would be relatively high, because of low surface coefficients of heat transfer on the shell side. A high metal temperature is undesirable for the apparatus under consideration because high metal temperatures are accompanied by higher rates of corrosion by the nitric acid.

A double-pipe heat exchanger was used to achieve a higher surface coefficient of heat transfer on the coolant side. With the higher heat-transfer coefficients the metal temperature of the inner tube through which the hot acid flows can be kept at a few degrees above the temperature of the coolant and consequently keeps the corrosion rate to a minimum. Figure 9 illustrates the type of heat exchanger being constructed.

Type 3S aluminum was selected as the metal for the tubes for the following reasons: (a) It has good resistance to nitric-acid corrosion, (b) its thermal conductivity is high, and (c) it is available in stock sizes and can be readily bent, machined, and welded.

The design calculations for one combination of acid conditions (at the entrance to the test section) are presented below:

Temperature of acid entering heated test section, $^{\circ}$F	100
Pressure on acid side, lb/sq in.	400
Reynolds number at inlet to test section	200,000
Heat added to acid in test section, Btu/hr	341,344
Assumed water temperature, $^{\circ}$F	75
Water flow available, gal/min	0-100

If water at 75° F is used as the coolant, calculations revealed that the most difficult cooling problem occurs at the above-listed conditions; that is, when the temperature of the acid entering the test section is 100° F (the lowest temperature considered for 75° F water), the acid weight flow is a maximum, and the heat input is a maximum. Since the coolant system is an independent system any suitable fluid may be employed as the coolant. Water will be used for tests where the temperature of the acid entering the section exceeds 100° F, and a mixture of dry ice and trichloroethylene, for low-temperature tests.

Calculations of the type shown below indicated that the tube sizes giving a satisfactory combination of heat-transfer characteristics and pressure drop are 1-inch outside diameter with 0.109-inch wall for the inner tube and $1\frac{1}{2}$-inch outside diameter with 0.095-inch wall for the outer tube.

Flow areas:

$$\text{1-inch tube} = 0.00334 \text{ sq ft}$$

$$\text{Annulus area } A = 0.00391 \text{ sq ft}$$

(1) Quantity of water to be circulated: Assuming a water flow of Q = 50 gallons per minute, the velocity of water V circulated is

$$\begin{aligned} V &= Q/A \\ &= \frac{50 \text{ gal}}{\text{min}} \times \frac{\text{min}}{60 \text{ sec}} \times \frac{\text{cu ft}}{7.48 \text{ gal}} \times \frac{1}{0.00391 \text{ sq ft}} \\ &= 28.5 \text{ ft/sec} \end{aligned}$$

The pressure drop on the water side at this velocity is too high to be supplied by the available two-stage water pump. The pump has the following characteristics: Capacity, 100 gallons per minute and head, 320 feet (139 lb/sq in.). It was decided to divide the water circuit into two equal parts, circulating 50 gallons per minute through each half of the exchanger. The calculations are made with water velocity of 28.5 feet per second (50 gal/min) and a water temperature rise of 6.8° F (100 gal/min).

(2) Water temperature rise:

$$\begin{aligned} \text{Heat removed} &= 100 \text{ kw} \\ &= 94.78 \text{ Btu/sec} \\ &= 341{,}200 \text{ Btu/hr} \end{aligned}$$

$$\Delta T = \frac{q}{W\bar{c}_p}$$

$$= \frac{94.78}{100 \times \frac{1}{60} \times \frac{1}{7.48} \times 62.2 \times 1.0}$$

$$= 6.8^{\circ}\ F$$

where

ΔT temperature rise, $^{\circ}F$

q rate of heat flow, Btu/sec

W weight rate of water flow, lb/sec

$\bar{c}_p$ average specific heat, Btu/lb/$^{\circ}F$

(3) Average water temperature:

$$T_{av} = T_{in} + \frac{T}{2} = 75 + \frac{6.8}{2} = 78.4^{\circ}\ F$$

(4) Surface coefficient of heat transfer (water side) h:

$$\begin{pmatrix}\text{Nusselt}\\ \text{number}\end{pmatrix} = \frac{hD_e}{k} = 0.023\begin{pmatrix}\text{Reynolds}\\ \text{number}\end{pmatrix}^{0.8}\begin{pmatrix}\text{Prandtl}\\ \text{number}\end{pmatrix}^{0.4}$$

(Equation taken from reference 13.)

Reynolds number R_e:

$$R_e = 93{,}000\ \frac{\rho D_e V}{\mu}$$

where

ρ density, grams/cc

D_e equivalent diameter, in.

V velocity, ft/sec

μ viscosity, centipoises

Equivalent diameter (taken from reference 14):

$$D_e = \frac{4 \times \text{Flow area}}{\text{Wetted perimeter}}$$

$$= \frac{D_2{}^2 - D_1{}^2}{D_1}$$

$$= \frac{1.310^2 - 1.00^2}{1.00}$$

$$= 0.712 \text{ in.}$$

$$R_e = 93,000 \times \frac{0.996 \times 0.716 \times 28.5}{12 \times 0.84} = 188,000$$

$$R_e{}^{0.8} = 16,000$$

Prandtl number Pr:

$$Pr = 2.42 \frac{c_p \mu}{k}$$

where

c_p specific heat, Btu/lb/°F

k thermal conductivity, Btu/(hr)(sq ft)(°F/ft)

$$Pr = \frac{2.42 \times 1 \times 0.84}{0.349} = 5.82$$

$$Pr^{0.4} = 2.02$$

Nusselt number Nu:

$$Nu = \frac{hD_e}{k}$$

$$= 0.023(R_e)^{0.8}(Pr)^{0.4}$$

$$= 0.023 \times 16{,}600 \times 2.02$$

$$= 770$$

$$h = \frac{k}{D_e}(770)$$

$$= \frac{0.349}{0.716} \times 12 \times 770$$

$$= 4500 \text{ Btu/(hr)(sq ft)(}^\circ\text{F)}$$

(5) Amount of acid cooled: Calculations indicate that the heat-transfer problem is more severe at the maximum weight flow (R_e = 200,000) than at the minimum weight flow (R_e = 60,000). When the inlet Reynolds number is 200,000 the weight flow is 2.87 pounds per second (fig. 2).

(6) Acid temperature rise in test section:

$$\text{Heat added} = 100 \text{ kw}$$

$$= 94.78 \text{ Btu/sec}$$

$$= 341{,}200 \text{ Btu/hr}$$

$$\Delta T = \frac{q}{Wc_p}$$

$$= \frac{94.78}{2.87 \times 0.44}$$

$$= 75^\circ \text{ F}$$

(7) Assuming that the average acid temperature can be used to calculate the surface coefficient, the average temperature is:

$$T_{av.} = 100 + \frac{75}{2} = 137.5^{\circ}\ F$$

(8) Surface coefficient of heat transfer (acid side):

Acid velocity:

$$V = \frac{W}{\gamma A}$$

$$= \frac{2.87}{1.43 \times 62.43 \times 0.00334}$$

$$= 9.63\ \text{ft/sec}$$

Reynolds number R_e:

$$R_e = 93,000\ \frac{\rho DV}{\mu}$$

$$= 93,000\ \frac{1.43 \times 0.782 \times 9.63}{12 \times 0.58}$$

$$= 144,000$$

$$R_e^{0.8} = 13,400$$

Prandtl number Pr:

$$Pr = 2.42\ \frac{c_p \mu}{k}$$

$$= \frac{2.42 \times 0.44 \times 0.58}{0.112}$$

$$= 5.52$$

$$Pr^{0.4} = 1.98$$

Nusselt number Nu:

$$Nu = 0.023\, R_e{}^{0.8} Pr^{0.4}$$

$$= 0.023 \times 13{,}400 \times 1.98$$

$$= 610$$

$$h = \frac{k}{D}(610)$$

$$= \frac{0.112}{0.782} \times 12 \times 610$$

$$= 1050 \text{ Btu/(hr)(sq ft)(}^{\circ}\text{F)}$$

(9) Log mean temperature difference:

$$\text{LMTD} = \frac{\Delta T_2 - \Delta T_1}{\log_e \dfrac{\Delta T_2}{\Delta T_1}}$$

where

ΔT_2 temperature difference between water and acid at acid inlet end

ΔT_1 temperature difference between water and acid at acid outlet end

$$\text{LMTD} = \frac{93 - 25}{\log_e 93/25} = \frac{68}{1.313} = 51.8$$

(10) Over-all coefficient of heat transfer based on outer tube surface:

$$\frac{1}{U} = \frac{A_{so}}{h_a A_{si}} + \frac{\Delta X A_{so}}{K_t A_{sw}} + \frac{A_{so}}{h_w A_{so}} + R_s$$

where

U over-all coefficient of heat transfer, Btu/(hr)(sq ft)(°F)

A_s surface area, sq ft

K_t thermal conductivity of tube, Btu/(hr)(sq ft)(°F/ft)

ΔX thickness of tube, ft

R_s scale factor

Subscripts:

o outer surface of tube

i inner surface of tube

w average surface of tube

The scale factor R_s was selected as 0.0005. This value is one-half the value recommended for Great Lakes well water in reference 15.

The use of the tabulated factors in a design is intended to insure that the exchanger does not deliver less than the required process heat load for a period of about a year to a year and a half. Since the actual operating time for the heat exchange will be less than a year, a value one-half of the recommended value was selected.

$$\frac{1}{U} = \frac{1}{1050 \times 0.782} + \frac{0.109 \times 1}{89.5 \times 12 \times 0.891} + \frac{1}{4500} + 0.0005$$

$$= 0.00122 + 0.000114 + 0.000222 + 0.0005$$

$$= 0.002056$$

$$U = 487 \text{ Btu/(hr)(sq ft)(°F)}$$

(11) Required surface area:

Fourier equation:

$$q = UA(\mathrm{LMTD})$$

$$A = \frac{q}{U(\mathrm{LMTD})} = \frac{341{,}200}{487 \times 51.8} = 13.5 \text{ sq ft}$$

(12) Length of tube:

$$\text{Area per foot} = 0.262 \text{ sq ft/ft}$$

$$L = \frac{13.5}{0.262} = 51.5 \text{ ft}$$

(13) Final design: The calculations presented were based on the most severe condition to be expected. The final design is an exchanger consisting of six tubes, each 8 feet long. The 8-foot length permits locating the exchanger along the south wall of the test cell. A dimensional sketch is presented in figure 9.

(14) Pressure drop (acid side): The equation and friction factor are from reference 16.

$$\Delta p = \frac{fL\gamma V^2}{16.1D}$$

where

Δp pressure drop, lb/sq ft

f Fanning coefficient of friction

L length, ft

γ specific weight, lb/cu ft

D diameter, ft

V velocity, ft/sec

$$f = \phi(R_e) = 0.0047$$

$$L = 6 \times 8 + \text{Bends} = 60.2 \text{ ft}$$

$$\Delta p = \frac{0.0047 \times 60.2 \times (1.43 \times 62.43) \times 9.63^2 \times 12}{16.1 \times 0.482}$$

$$= 2250 \text{ lb/sq ft}$$

$$= 15.6 \text{ lb/sq in.}$$

(15) Pressure drop (water side): Pressure drop due to fluid friction on the water side is a combination of the inner-wall resistance of the outer pipe and the outer surface of the inner pipe. The total wetted perimeter is $\pi(D_2 - D_1)$ and for the pressure drop in annuli (reference 14),

$$D_e' = \frac{4 \times \text{Flow area}}{\text{Frictional wetted perimeter}}$$

$$= \frac{4\pi(D_2{}^2 - D_1{}^2)}{4\pi(D_2 - D_1)}$$

$$= D_2 - D_1$$

$$= 1.310 - 1.000$$

$$= 0.310 \text{ in.}$$

$$R_e = R_e \times \frac{D_e'}{D_e} = 188{,}000 \times \frac{0.310}{0.716} = 81{,}300$$

$$f = \phi(R_e) = 0.005$$

The length of one-half of the exchanger:

$$L = 3 \times 8 + \text{Connectors} = 29.2 \text{ ft}$$

$$\Delta p = \frac{fL\gamma V^2}{16.1 D_e'}$$

$$= \frac{0.005 \times 29.2 \times (0.996 \times 6243) \times 28.5^2 \times 12}{16.1 \times 0.310}$$

$$= 123 \text{ lb/sq in.}$$

APPENDIX C

HEAT GENERATION IN TEST-SECTION TUBE

Reference 17 presents two convenient equations expressing the heat flux in a hollow tube

$$\xi = \frac{E^2 \times 10^{-3}}{1.045 \times 10^{-3} L} \frac{t(D + t)}{DT} \tag{C1}$$

or

$$\xi = \frac{0.948P}{DL} \tag{C2}$$

where

E electromotive force across the tube

ξ electrical resistivity, ohms/in.

L length of tube, in.

D inside diameter of tube, in.

t thickness of wall, in.

P power input, kw

Equations (C1) and (C2) have been used to calculate the data for a series of graphs presented in figure 14 which can be used to determine the amperage and voltage necessary to obtain a given heat-flux density. An example of the use of the graphs in figure 14 is presented below. The data used in this example are the specifications of the test section to be used in the apparatus:

Tube length, in.	24
Tube inside diameter, in.	0.539
Tube wall thickness, in.	0.043
Heat flux, Btu/sec/sq in.	1.5
Tube temperature, $^{\circ}$F	700

Resistivity of H.S. 25:

$$\rho = 34.9(1 + 0.00062t)$$

where t is temperature; therefore,

$$\rho = 34.9(1 + 0.434) = 50.1 \text{ microhms/in.}$$

Step I. Using the wall thickness and the inside diameter locate point a.

Step II. Project point a vertically until the projection line crosses the heat-flux line of 1.5 Btu per second per square inch and thus determine point b.

Step III. Project point b horizontally until it intersects with the 50-microhm resistivity line which determines c.

Step IV. Calculate the power input necessary

$$P = \frac{L\xi\pi D}{0.9478} = \frac{24 \times 1.5 \times \pi \times 0.539}{0.948} = 64.4 \text{ kw}$$

Step V. Project point c until it crosses the curve for a 64.4-kw power input. The amperage indicated is 2070 and the voltage is 31.

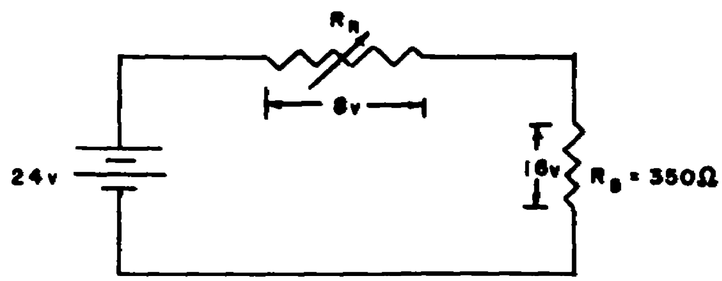
APPENDIX D

INSTRUMENTATION OF ACID FLOW MEASUREMENT

Three orifice plates of different throat diameters are necessary to meter the acid flow over the complete range; all three orifice plates are designed for a maximum differential pressure of 25 pounds per square inch. The same Statham transducer will be used for measuring the differential pressure across each orifice plate.

Figure 15 is a schematic diagram of the electrical circuit to be used with the Statham differential-pressure transducer. For accurate readings a hand-balanced potentiometer will be used for measuring the electrical output from the transducer, whereas a microammeter will be used as a continuous indicator.

The power supply to the transducer comprises four 6-volt storage batteries. For the purpose of maintaining a constant 16-volt input to the transducer, during the lift of the batteries, the battery circuit is equipped with variable resistances. The figure presented below is a simplified battery circuit diagram.



From an analysis of the above circuit a maximum resistance of 175 ohms is required in the battery circuit. The variable resistance will be adjusted until a predetermined potential drop occurs across the calibrating resistance shown in figure 15. According to recommendations of the Statham Laboratories, the calibrating resistance is 30,000 ohms.

To achieve control accuracy of the regulating resistance which is commensurate with the accuracy of the potentiometer, the following arrangement of the regulating resistance has been chosen. The resistance will be made up of three elements:

(1) A 60-ohm constant resistor

(2) A 100-ohm variable resistor for rough setting

(3) A 30-ohm variable resistor for fine setting

APPENDIX E

MEASUREMENT OF PRESSURE DROP THROUGH TEST-SECTION TUBE

The electrical circuit for measuring the frictional pressure drop for the test section is almost identical with that used for measuring the differential pressure across the orifice plate (see appendix D). The only significant differences in the two circuits are (a) the difference in the pressure range of the transducer and (b) the introduction of a Sensitrol unit in the circuit.

Transducer

Calculations of the maximum pressure drop to be expected in the test section indicated that the maximum differential pressure will not exceed 20 pounds per square inch. Consequently, a transducer designed for pounds-per-square-inch operating pressure was selected; the transducer is capable, however, of handling differential pressures up to a maximum of 50 pounds per square inch, but the accuracy of the instrument decreases for pressures above 20 pounds per square inch.

Calculation of pressure drop through the test section is given below.

Maximum acid velocity:

$$V = \frac{Q}{A}$$

$$= \frac{30 \text{ gal/min}}{\frac{0.228}{144} 7 \times 48 \times 60}$$

$$= 42 \text{ ft/sec}$$

Maximum pressure drop in test section: Using the Fanning equation,

$$\Delta p = (\gamma)(f)\left(\frac{L}{D}\right)\left(\frac{V^2}{2g}\right)$$

where

f friction factor (Data on seamless aluminum tubing was used for friction factor.)

V velocity, ft/sec

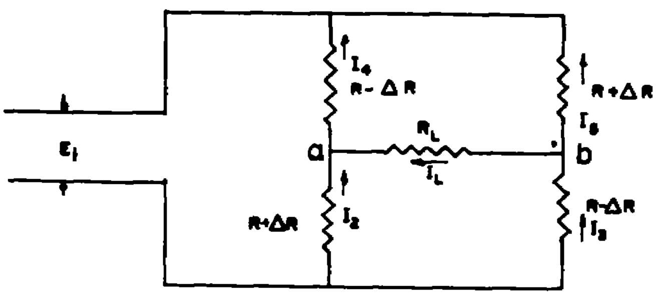
L/D ratio of length to diameter

$$\Delta p = 1.59 \times 62.4 \times 0.0175 \times \frac{24}{0.539} \times \frac{42^2}{64.34 \times 144}$$

$$= 14.75 \text{ lb/sq in.}$$

Sensitrol and Attenuator Circuit

To design the Sensitrol circuit, it is necessary to have an equation for the output obtained from a stressed strain gage bridge of a transducer.



The symbol E_i is input to the Statham transducer and the subscript L refers to the load due to the stressing of the bridge.

The potential drop across the strain gage can be expressed as the sum of the potential drops in branches 2 and 4.

$$E_i = I_2(R + \Delta R) + I_4(R - \Delta R) \tag{E1}$$

Considering a current balance at a

$$I_2 = I_4 - I_L \tag{E2}$$

$$E_1 = 2I_4R - I_L(R + \Delta R) \tag{E3}$$

Employing Kirchoff's law:

$$I_LR_L + I_3(R - \Delta R) = I_2(R + \Delta R) \tag{E4}$$

But at point b

$$I_3 = I_5 + I_L \tag{E5}$$

Substituting equations (E2) and (E5) in equation (E4)

$$I_LR_L + I_5(R - \Delta R) + I_L(R - \Delta R) + I_L(R + \Delta R) = I_4(R + \Delta R) \tag{E6}$$

Equation (E6) can be simplified to

$$I_L(2R + R_L) - I_4(R + \Delta R) + I_5(R - \Delta R) = 0 \tag{E7}$$

Employing Kirchoff's law again

$$I_LR_L + I_4(R - \Delta R) - I_5(R + \Delta R) = 0 \tag{E8}$$

Adding equations (E7) and (E8) gives

$$I_L(R + R_L) - I_4\ \Delta R - I_5\ \Delta R = 0 \tag{E9}$$

Subracting equation (E8) from (E7)

$$I_5 = I_4 - I_L \tag{E10}$$

Substituting equation (E10) in (E9) and solving for I_4

$$I_4 = I_L\frac{(R + \Delta R + R_L)}{2\Delta R} \tag{E11}$$

Substituting equation (E11) in (E3)

$$E_i = I_L\left[\frac{R\left(1 + \frac{\Delta R}{R} + \frac{R_L}{R}\right)}{\frac{\Delta R}{R}} - R\left(1 + \frac{\Delta R}{R}\right)\right] \tag{E12}$$

Consequently,

$$I_L = \frac{E_i \frac{\Delta R}{R}}{R\left(1 + \frac{\Delta R}{R} + \frac{R_L}{R}\right) - \Delta R\left(1 + \frac{\Delta R}{R}\right)} \tag{E13}$$

Therefore

$$E_L = I_L R_L$$

$$= \left\{\frac{E_i \frac{\Delta R}{R}}{R\left[1 - \left(\frac{\Delta R}{R}\right)^2\right] + R_L}\right\}$$

$$= \frac{E_i \frac{\Delta R}{R}}{\frac{R}{R_L}\left[1 - \left(\frac{\Delta R}{R}\right)^2\right] + R_L}$$

$$= \frac{E_i \frac{\Delta R}{R}}{1 + \frac{R}{R_L}\left[1 - \left(\frac{\Delta R}{R}\right)^2\right]} \tag{E14}$$

If second-order terms are neglected

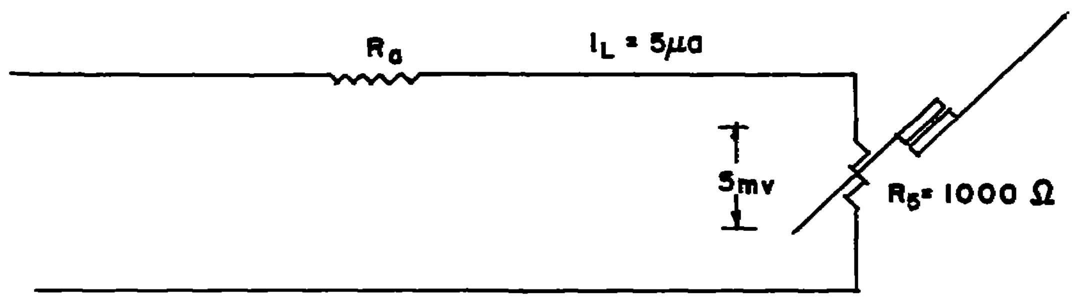
$$E_L = \frac{E_i \frac{\Delta R}{R}}{1 + \frac{R}{R_L}} \tag{E15}$$

Equation (E15) expresses the relationship between the output potential from the transducer and the input potential to the transducer.

The output potential from the transducer is connected to a Sensitrol unit which is set to trip a safety relay when 5 millivolts are imposed on the Sensitrol. Since the output of the transducer exceeds 5 millivolts, it is necessary to install a potential reducing resistance or attenuator between the transducer and the Sensitrol. By means of the attenuator it is possible to establish the limiting pressure drop that is to be tolerated through the test section.

Although the transducer is designed to indicate differential pressures accurately up to 20 pounds per square inch, the instrument will stand overload pressures up to 50 pounds per square inch. The Statham Laboratories notes indicate that the value of $E_i \frac{\Delta R}{R}$ for 20 pounds per square inch is 35 millivolts. Assuming linearity between the differential pressure and the electrical output from the transducer, the value of $E_i \frac{\Delta R}{R_L}$ at 50 pounds per square inch is 87.5 millivolts. Thus the maximum output from the transducer will be of the order of 88 millivolts and the attenuator needs to be of sufficient capacity to reduce the output to 5 millivolts.

Calculation of the attenuator resistance R_a is given below.



$$I_L = \frac{E_L}{R_L} = \frac{E_i \frac{\Delta R}{R}}{1 + \frac{350}{R_L}} = 5 \text{ microamperes}$$

$$I_L = \frac{\frac{87{,}500}{1 + \frac{350}{R_L}}}{R_L} = 5 \text{ microamperes} \qquad \text{(E16)}$$

Solving for R_L

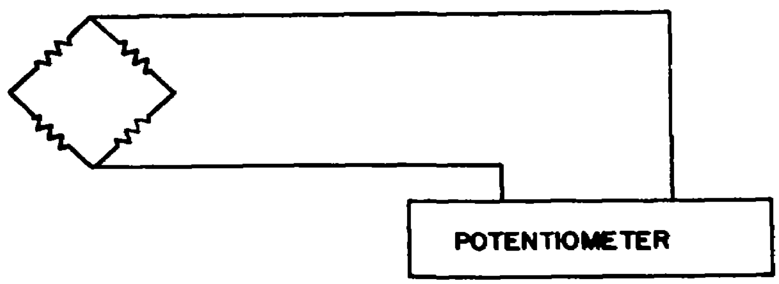
$$R_L = 17,150 \text{ ohms}$$

But,

$$R_L = R_a + R_5 = R_a + 1000$$

consequently the attenuator resistance is approximately 16,000 ohms.

Although the potentiometer indicating the pressure drop across the test section will be calibrated in pressure units, an equation expressing the relationship between the transducer output and the differential pressure can be derived easily.



Employing equation (E16)

$$R_L = \frac{\Delta p}{100} \times 35,000 - 350 \tag{E17}$$

Assuming that the differential pressure and the electrical output of the transducer are linear, equation (E15) can be rewritten

$$E_L = \frac{\frac{\Delta p}{20} \times 35}{1 + \frac{350}{R_L}} \tag{E15a}$$

Substituting equation (E17) in (E15a)

$$E_L = 1.75(\Delta p - 1) \tag{E18}$$

Equation (E18) expresses the relationship between the output of the transducer and the differential pressure in pounds per square inch across the test section.

APPENDIX F

METHOD OF LIMITING TEST-SECTION TEMPERATURE

Figure 16 is a circuit diagram for the test-section temperature safety control showing the method of connecting two parallel-connected thermocouples to a Sensitrol unit.

The electromotive force of the thermocouples at high tube surface temperatures is sufficient to cause the Sensitrol relay to actuate and thus bring about a shutdown of the electrical power. By placing a variable resistance in the circuit and conducting a calibration it is possible to fix the maximum tube temperature to be tolerated.

APPENDIX G

SAFETY RELAYS

Figure 17 is a wiring diagram showing how the pressure-actuated sensitrol and the temperature-actuated Sensitrol are connected to the safety relays, which are capable of shutting down the apparatus. To help clarify the diagram, the function of each relay will be briefly explained.

Relays A and B - pressure-drop control.- The current-carrying capacity of the Sensitrol sensitive to the frictional pressure drop is limited to 50 milliamperes, which is too low to operate the heavy-duty relay B necessary to shut the Annin valves and to shut down the acid pump and the electrical input to the tube. Relay A is a sensitive relay which can be operated by the Sensitrol output and can carry enough current to actuate relay B. As an additional safety feature relay B has a latching magnet which locks the relay in the open position after an automatic shutdown has occurred. This feature prevents a restart of the apparatus without a manual reset of the latching relay.

Relay C - tube temperature control.- In appendix F the Sensitrol circuit for the tube temperature control was described. Relay C, which is a single-throw, single-pole relay that amplifies the Sensitrol output, is capable of shutting down the electrical power to the test section when the surface temperature of the tube exceeds a fixed value.

Exciter control.- The exciter control consists of a breaker relay which is operated by relay C and a resistance to dissipate the exciter energy.

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TABLE I.- MATERIALS SUITABLE FOR USE WITH NITRIC ACID[1]

Designation	Materials
1A	Commercially pure aluminum, Type 2S
1B	High-purity aluminum (containing up to 99.85 percent Al)
1C	Aluminum-manganese alloy (containing 1.2 percent Mn), Type 3S
1E	Aluminum-magnesium silicide alloy (containing 0.7 percent Si, 1.3 percent Mg, and 0.25 percent Cr), Type 53S
1F	Aluminum-silicon alloys (containing 5 to 12 percent Si), Types 43 and 13
3A	High-silicon cast irons (not less than 14.25 percent Si)
3B	High-silicon cast iron (not less than 14.25 percent Si, approximately 3 percent Mo)
7A	Stainless steel - ferritic (15 to 18 percent Cr and 0.15 percent C (max.)), AISI Types 430 and 430F
7B	Stainless steel - ferritic (23 to 28 percent Cr and 0.25 percent C (max.)), AISI Type 446
8A	Stainless steel - austenitic (18 to 20 percent Cr, 8 to 10 percent Ni, and 0.08 percent C (max.)), AISI Types 304, 321, and 347
8B	Stainless steel - austenitic (17.5 to 20 percent Cr, 10 to 14 percent Ni, 2 to 4 percent Mo, and 0.10 percent C (max.)), Types 316 and 317
8C	Stainless steel - austenitic (22 to 24 percent Cr, 12 to 15 percent Ni, and 0.20 percent C (max.)), AISI Types 309 and 309S
8D	Stainless steel - austenitic (24 to 26 percent Cr, 19 to 22 percent Ni, and 0.25 percent C (max.)), AISI Type 310
9A	Special iron-chromium-nickel alloy - austenitic (19 to 20 percent Cr, 22 to 24 percent Ni, 2 to 3 percent Mo, 1.0 to 1.75 percent Cu, 1.0 to 3.25 percent Si, and 0.07 percent C)
9B	Special iron-chromium-nickel alloy - austenitic (20 percent Cr, 29 percent Ni, 2 percent Mo, 4 percent Cu, 1.0 percent Si, and 0.07 percent C)
20A	Tantalum
20B	Platinum and platinum alloys
20C	Gold
22A	Glass
22B	Porcelain
22C	Chemical stoneware

[1]Information taken from reference 10.

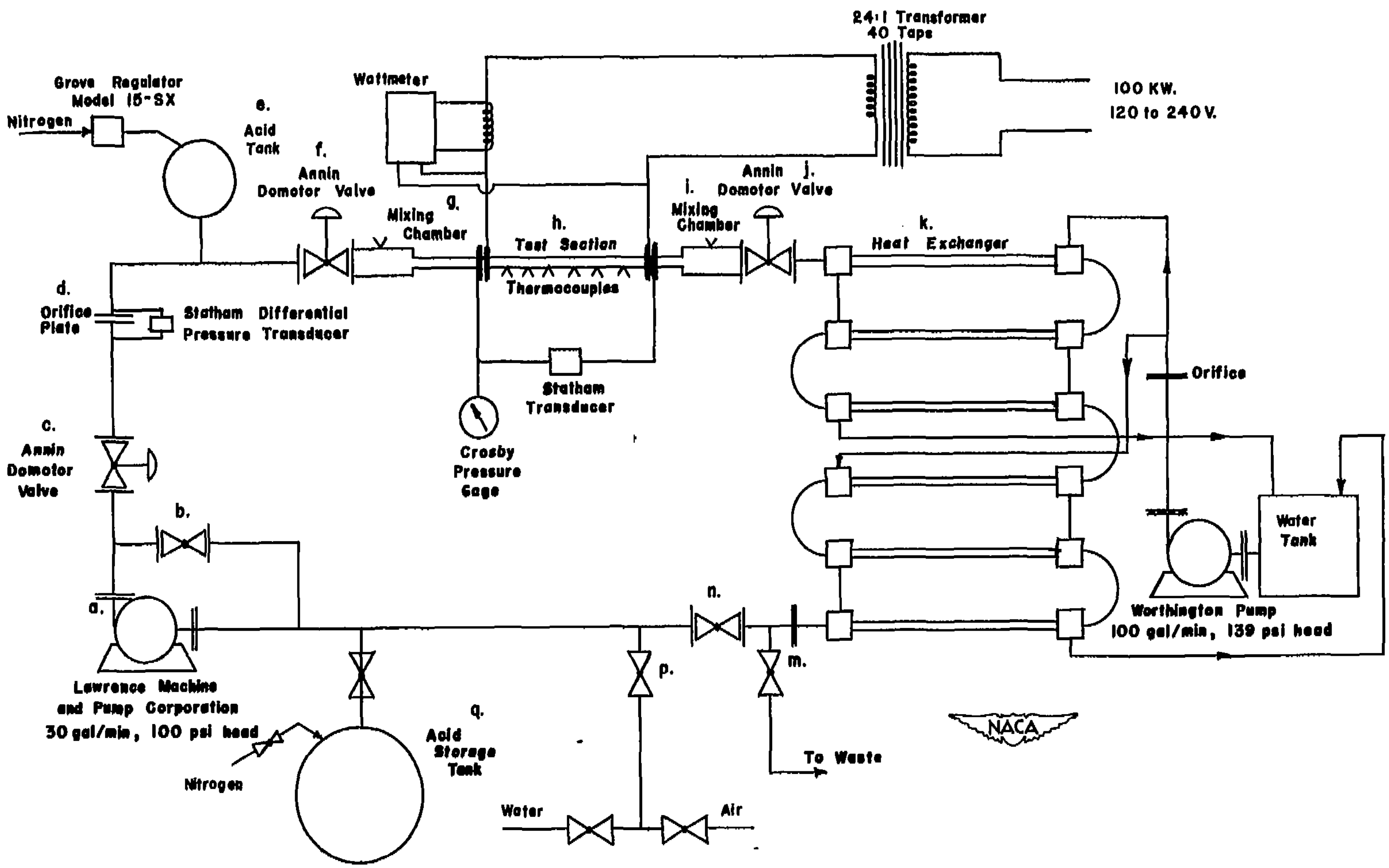

Figure 1.- Schematic diagram of test apparatus.

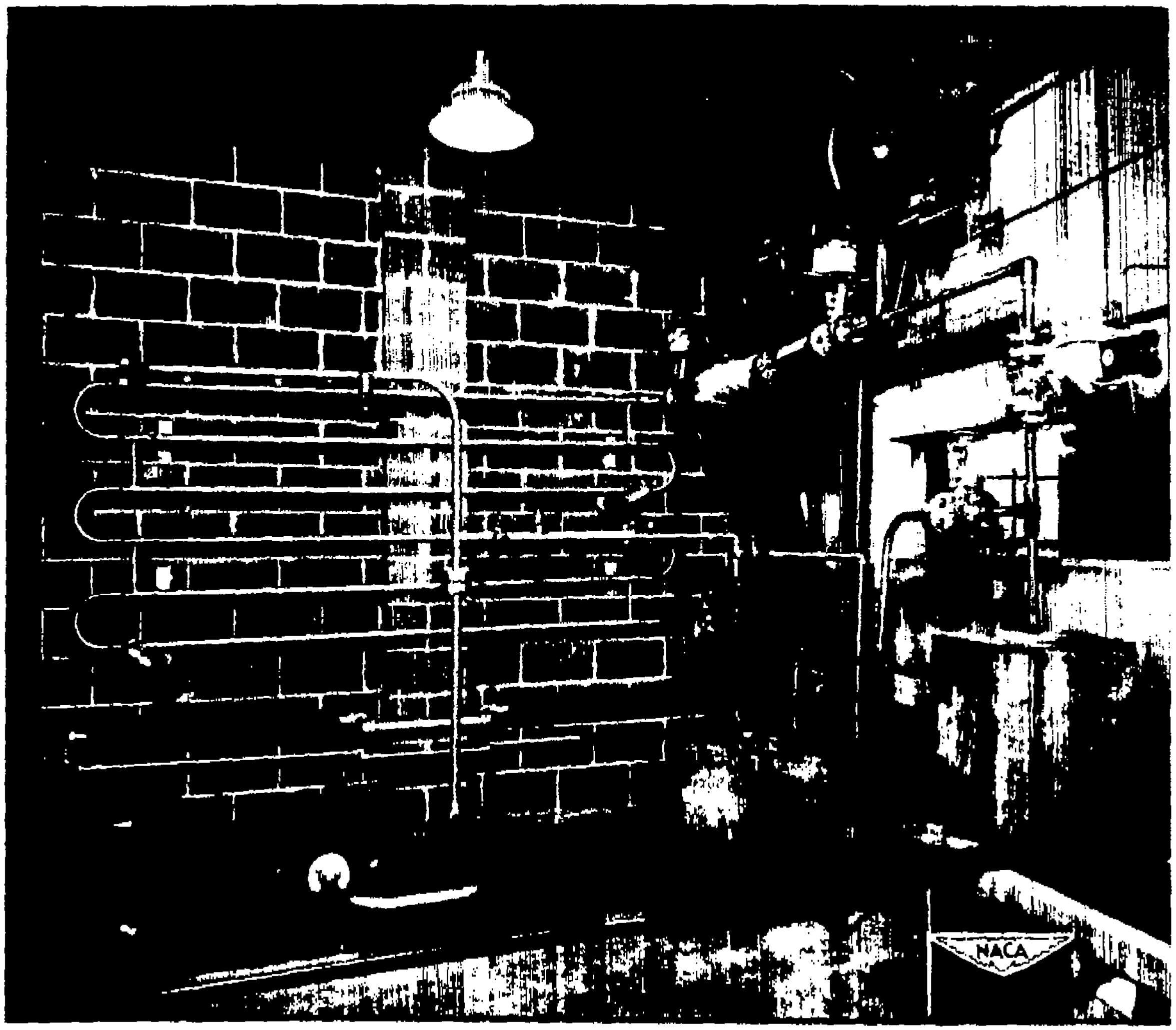

Figure 2.- Prospective view of apparatus before installation of acid pump.

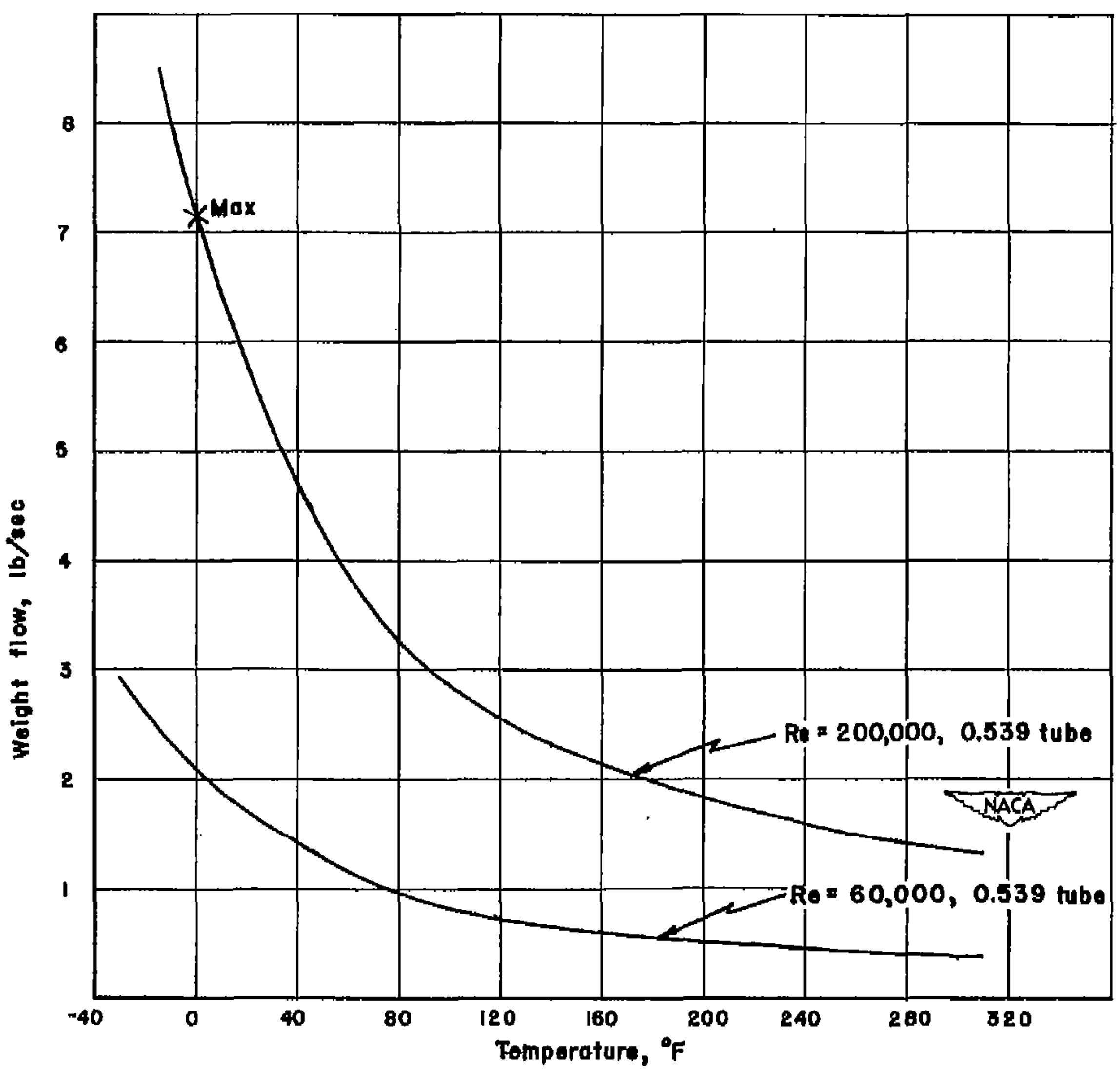

Figure 3.- Weight flow of nitric acid.

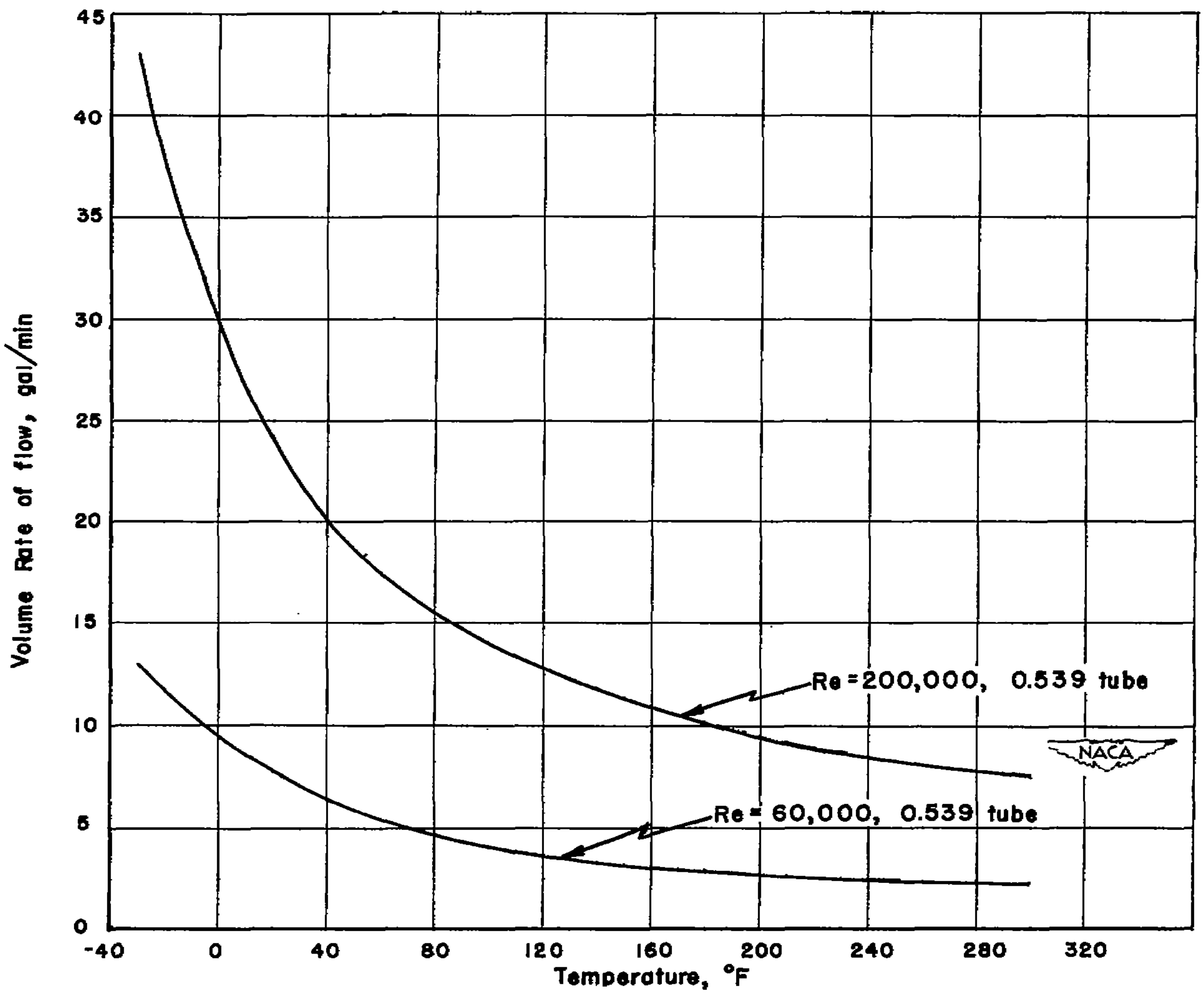

Figure 4.- Volume flow of nitric acid.

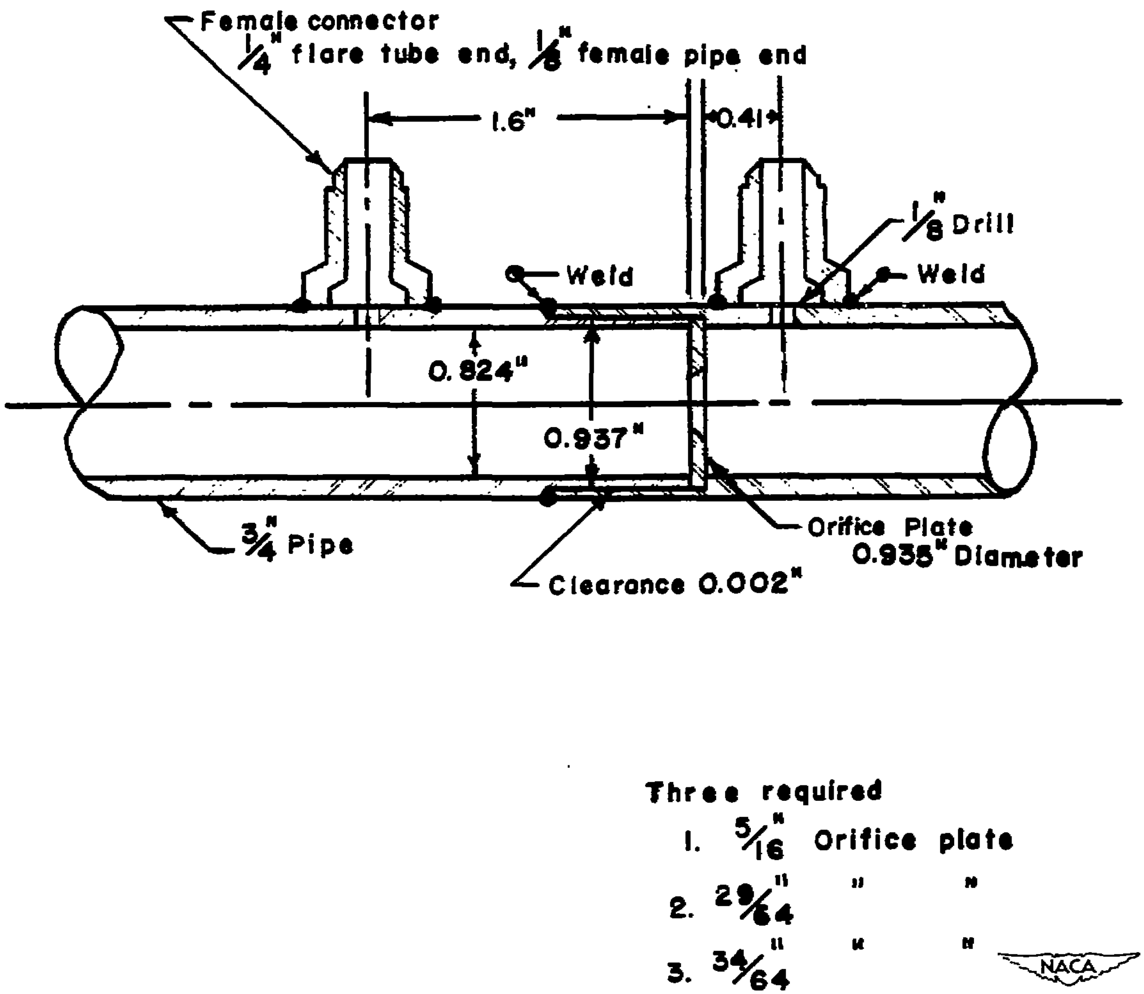

Figure 5.- Orifice meter.

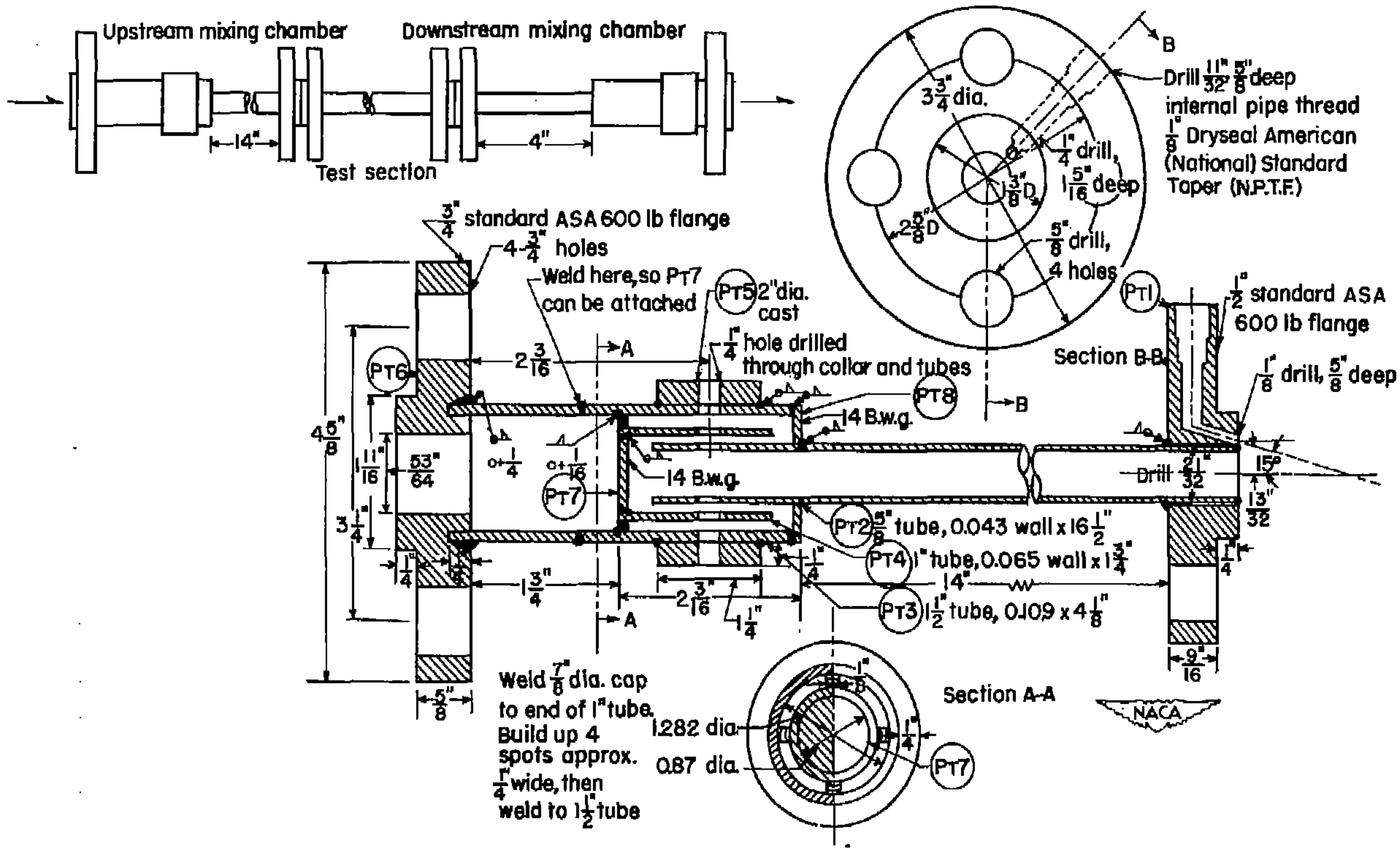

Figure 6.- Design for upstream mixing chamber made of H.S. 25. Revised in accordance with suggestions from the Haynes Stellite Company.

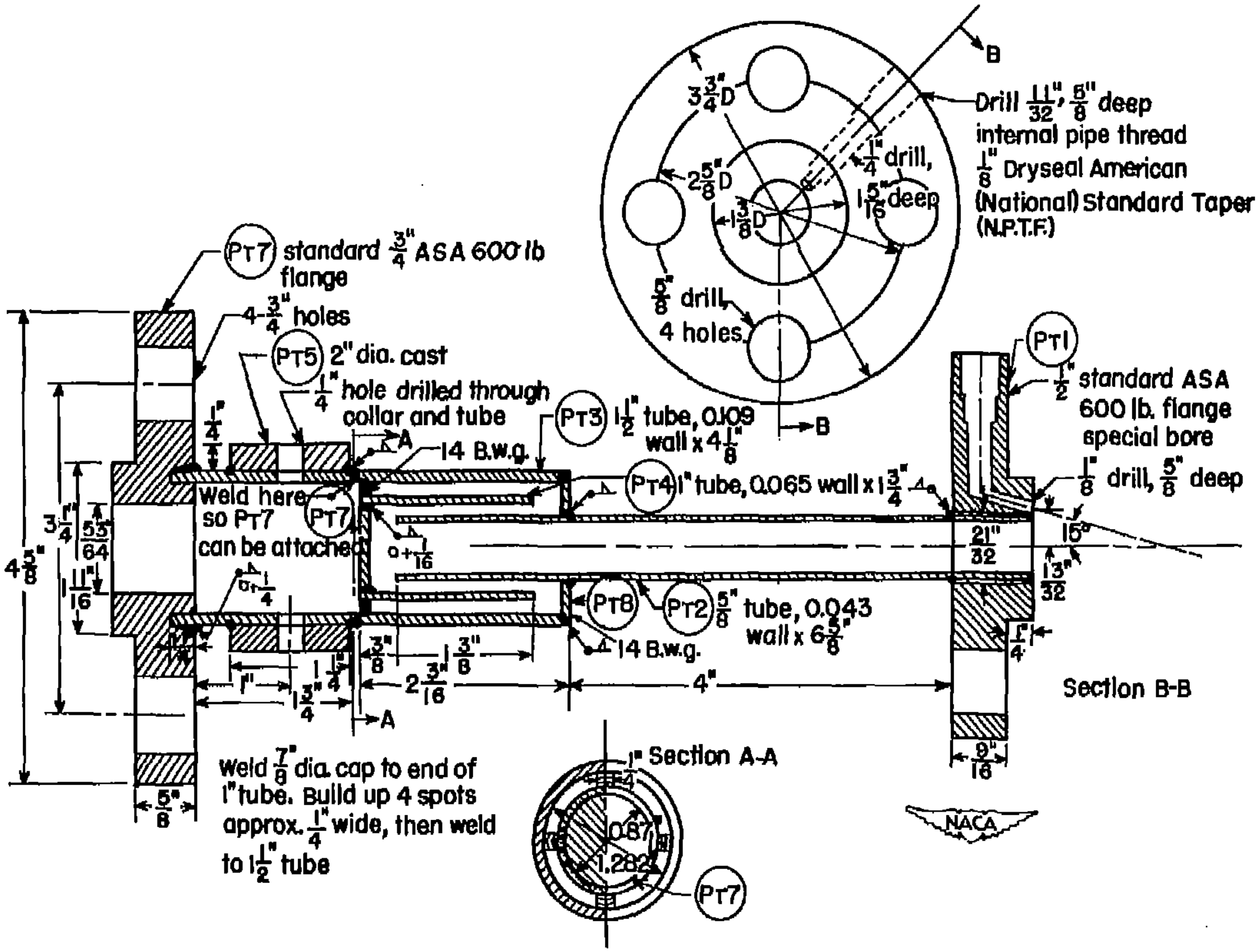

Figure 7.- Design for downstream mixing chamber made of H.S. 25. Revised in accordance with suggestions from the Haynes Stellite Company. Upstream and downstream chambers are identical except for length of part 2 and location of part 5.

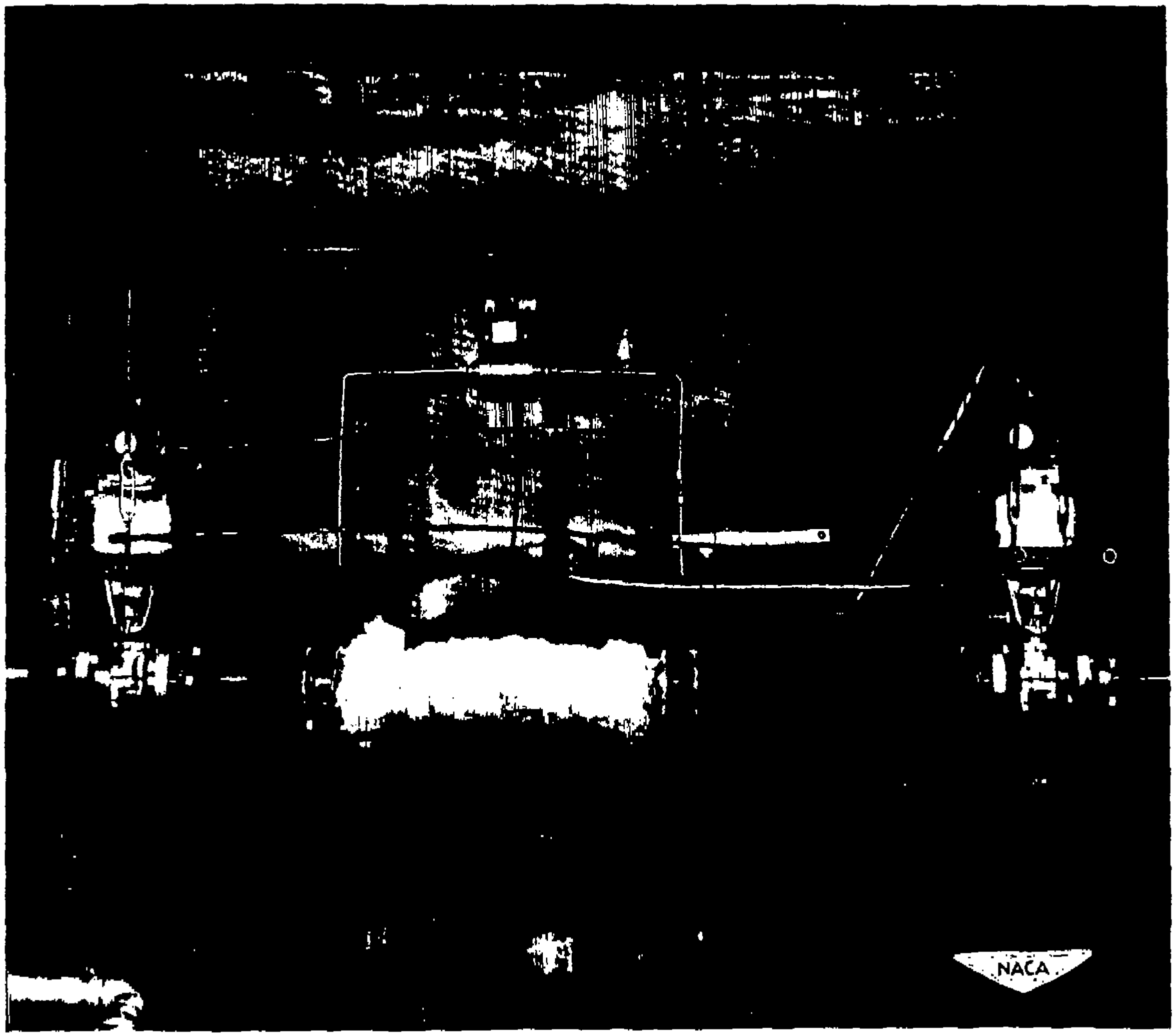

Figure 8.- Illustration of test section showing mixing chambers and safety valves.

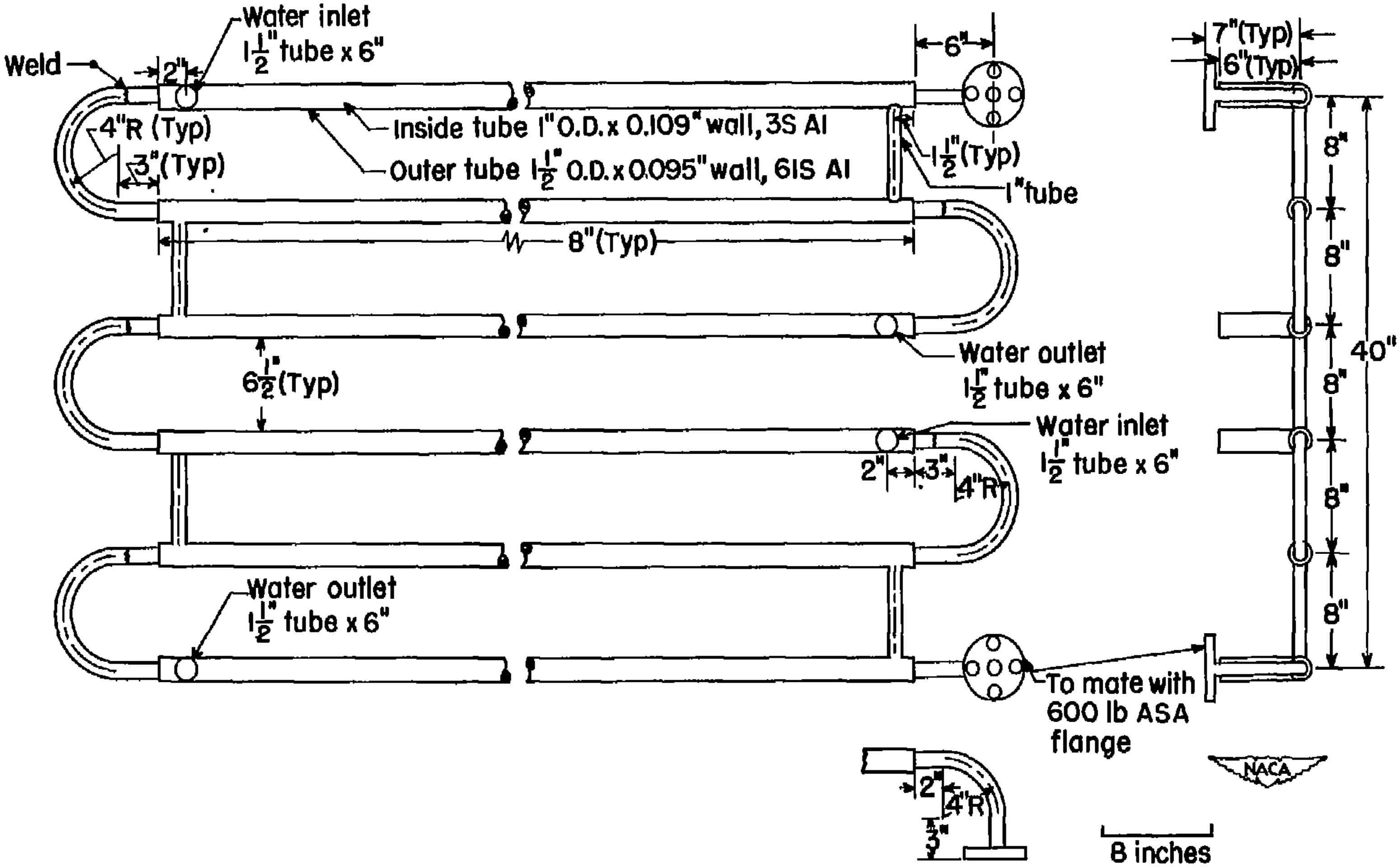

Figure 9.- Heat exchanger. All welding to be Heliarc; 1-inch tube circuit tested to 600 pounds per square inch and $1\frac{1}{2}$-inch tube circuit tested to 150 pounds per square inch.

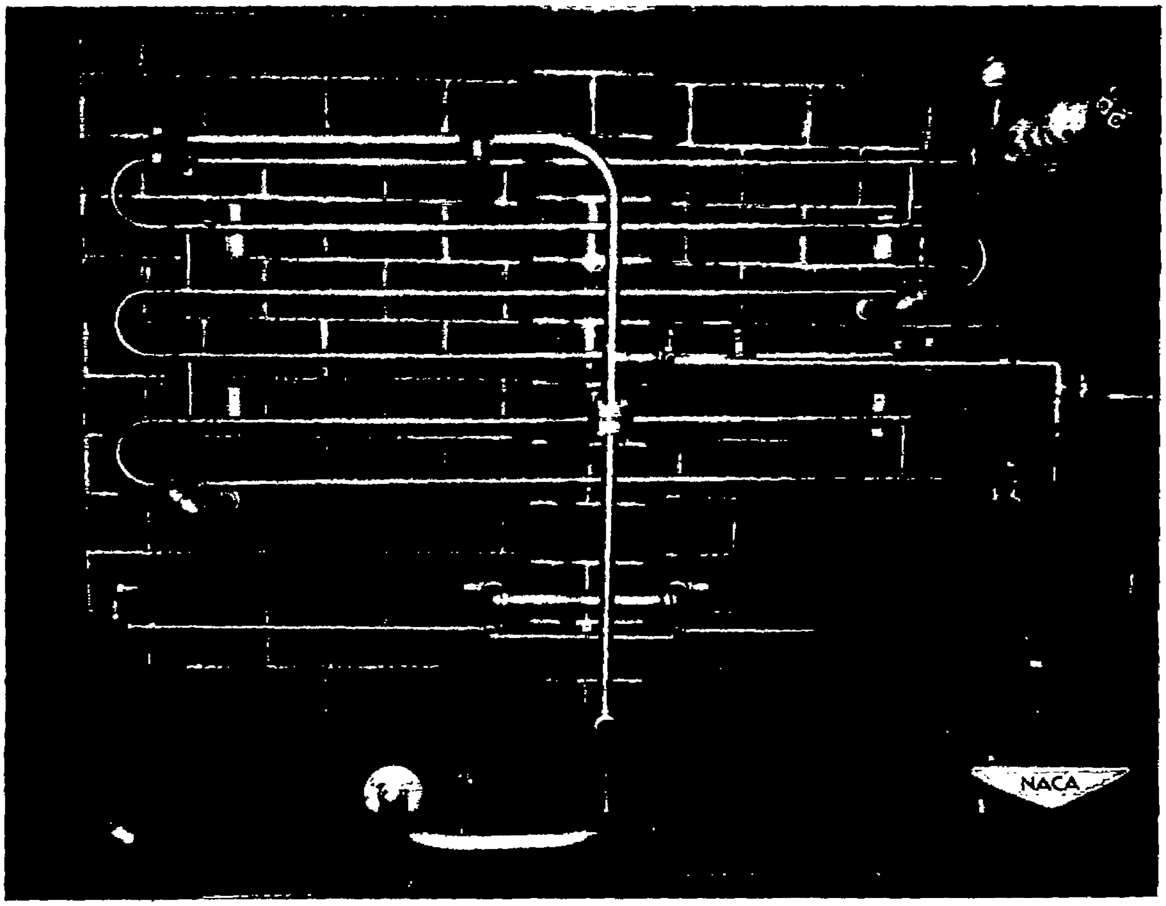

Figure 10.- Illustration of heat exchanger and pump for cooling water.

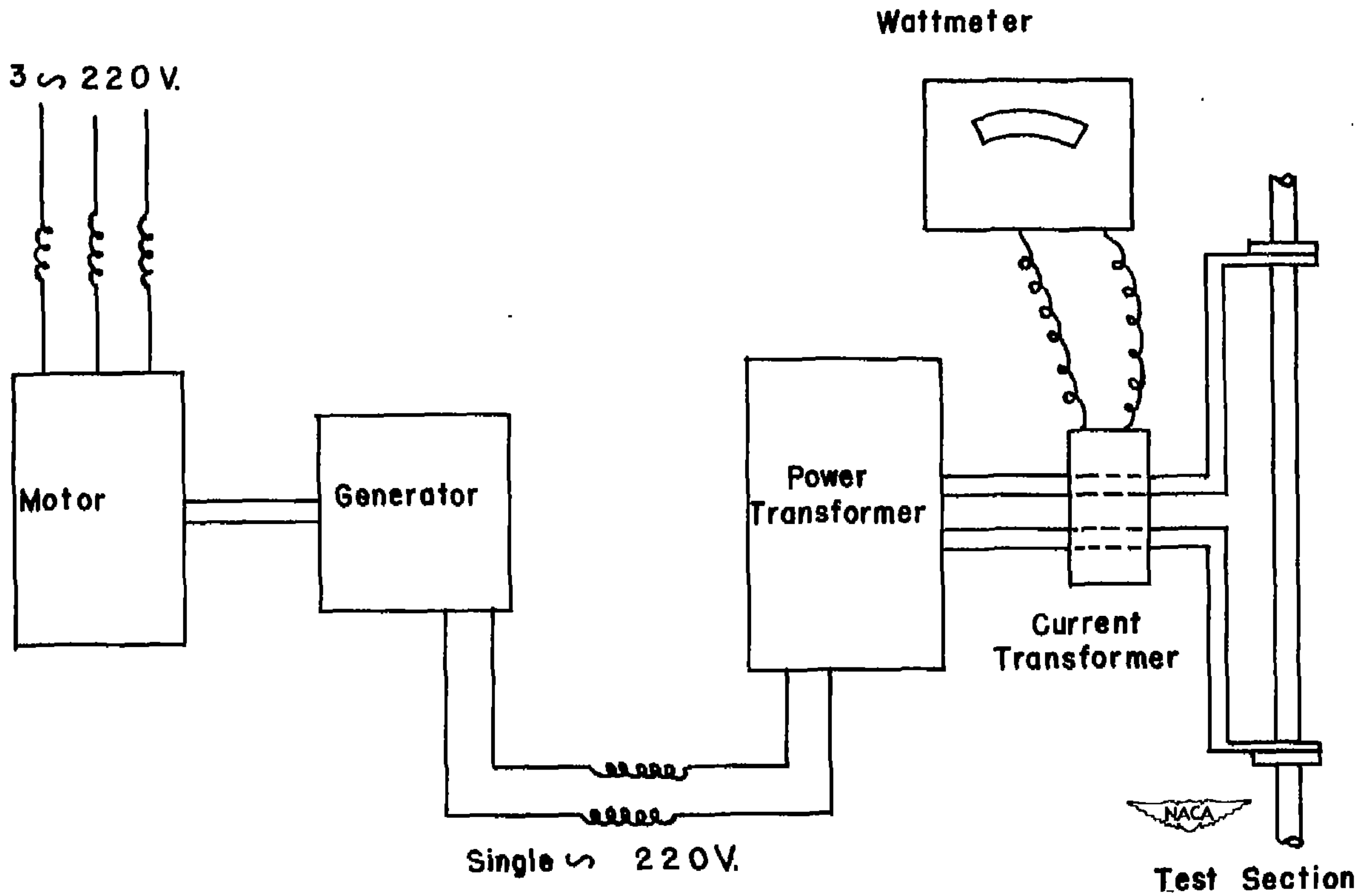

Figure 11.- Schematic diagram of electrical heating of H.S. 25 tube test section.

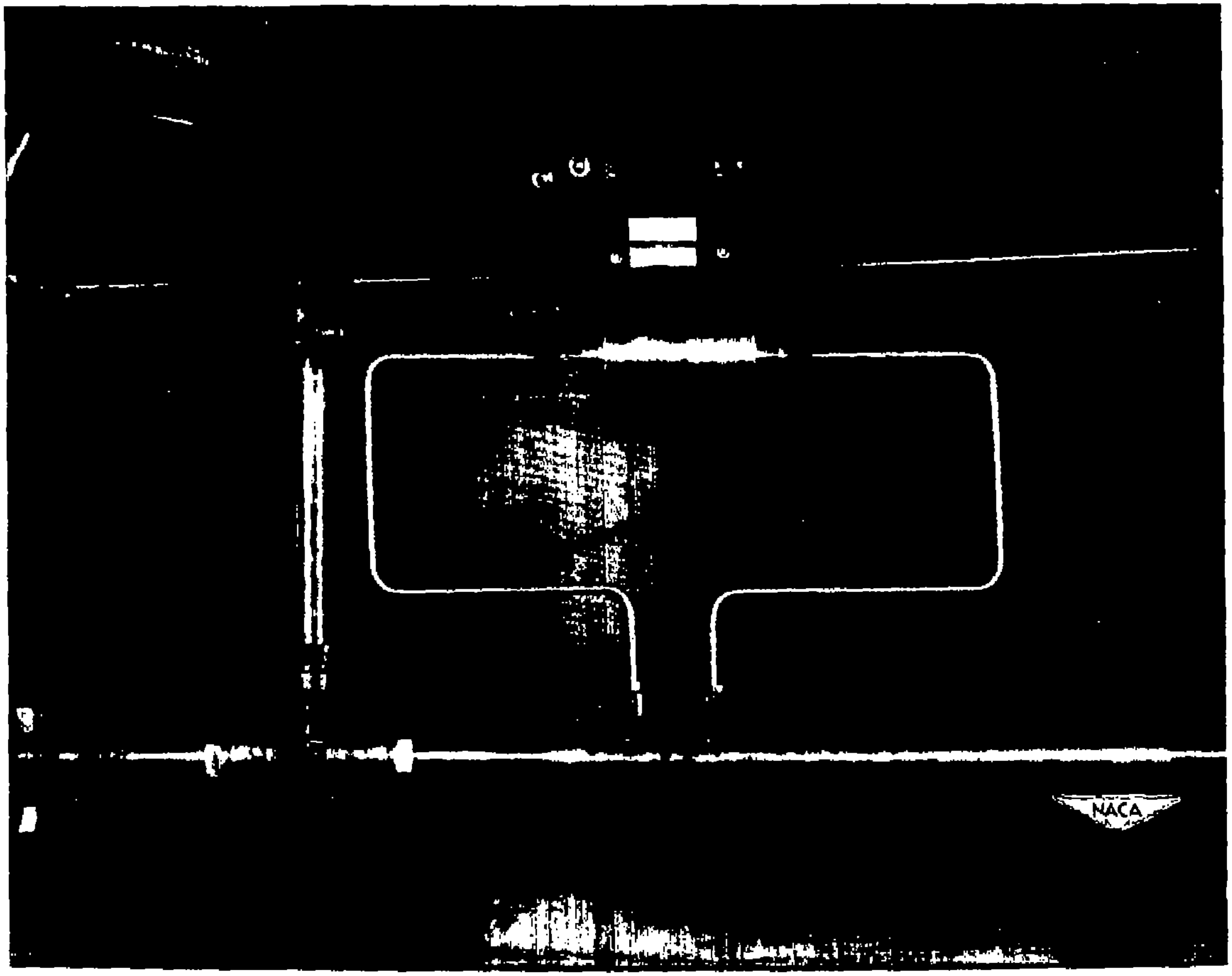

Figure 12.- Acid flow meter and Statham differential-pressure transducer.

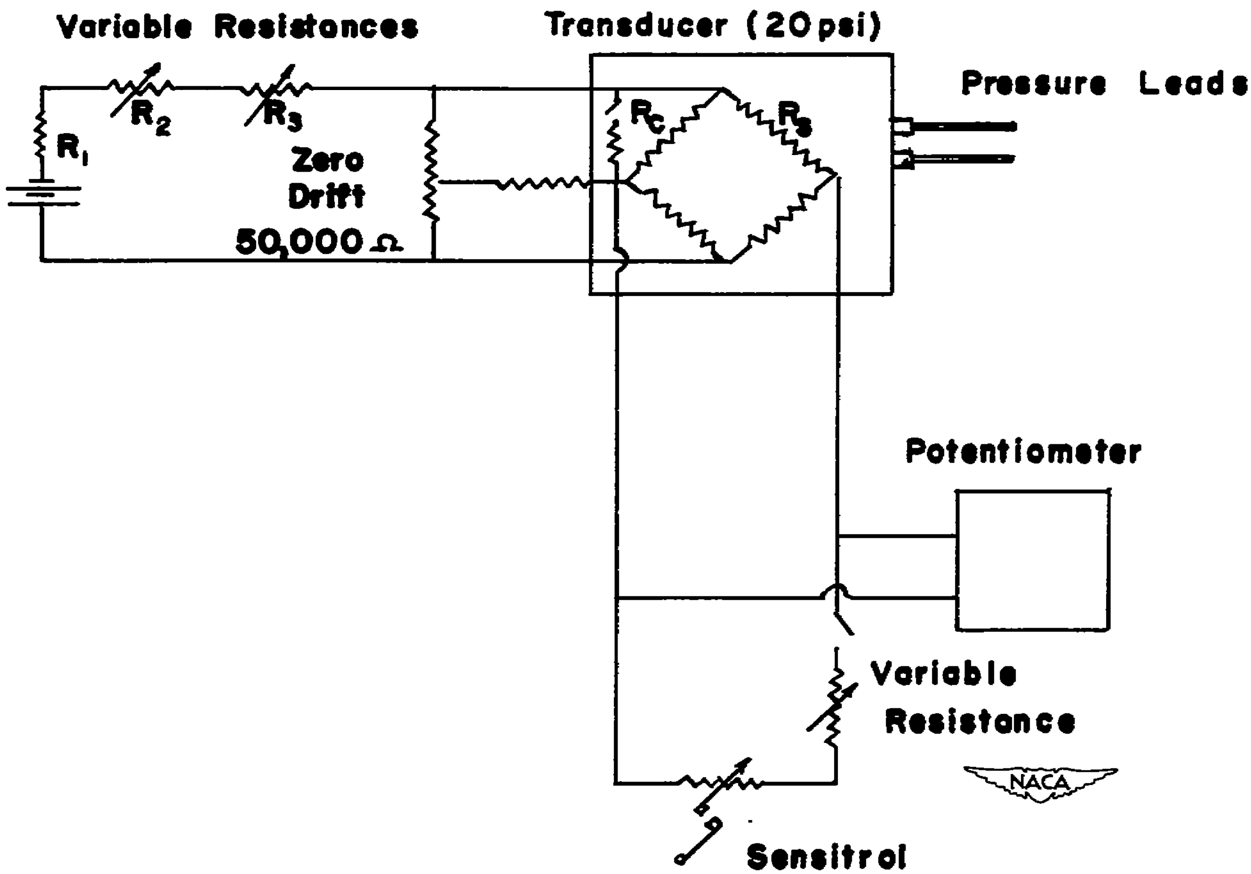

Figure 13.- Pressure measurement and safety pressure control.

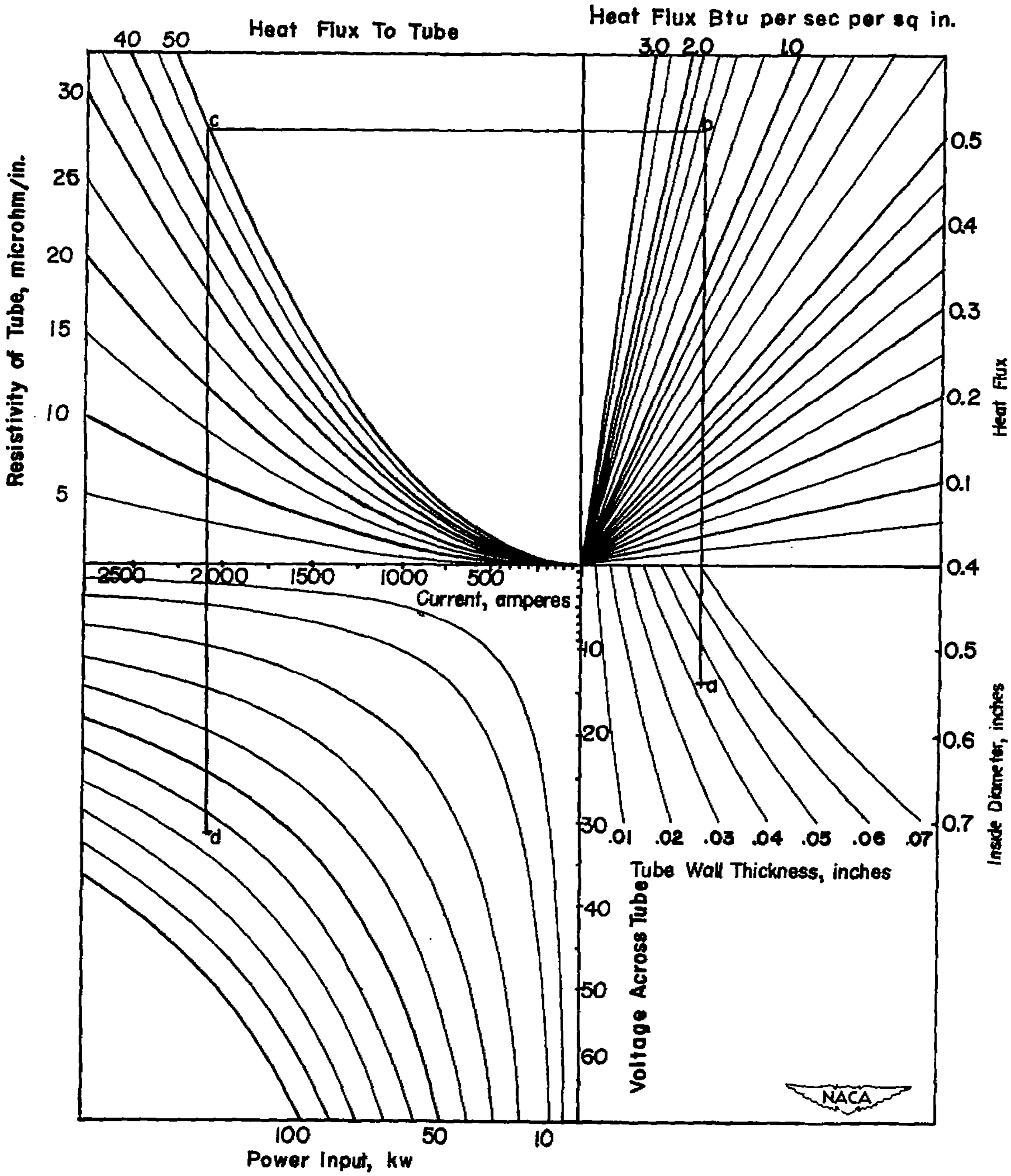

Figure 14.- Calculation chart for heat flux to hollow tube.

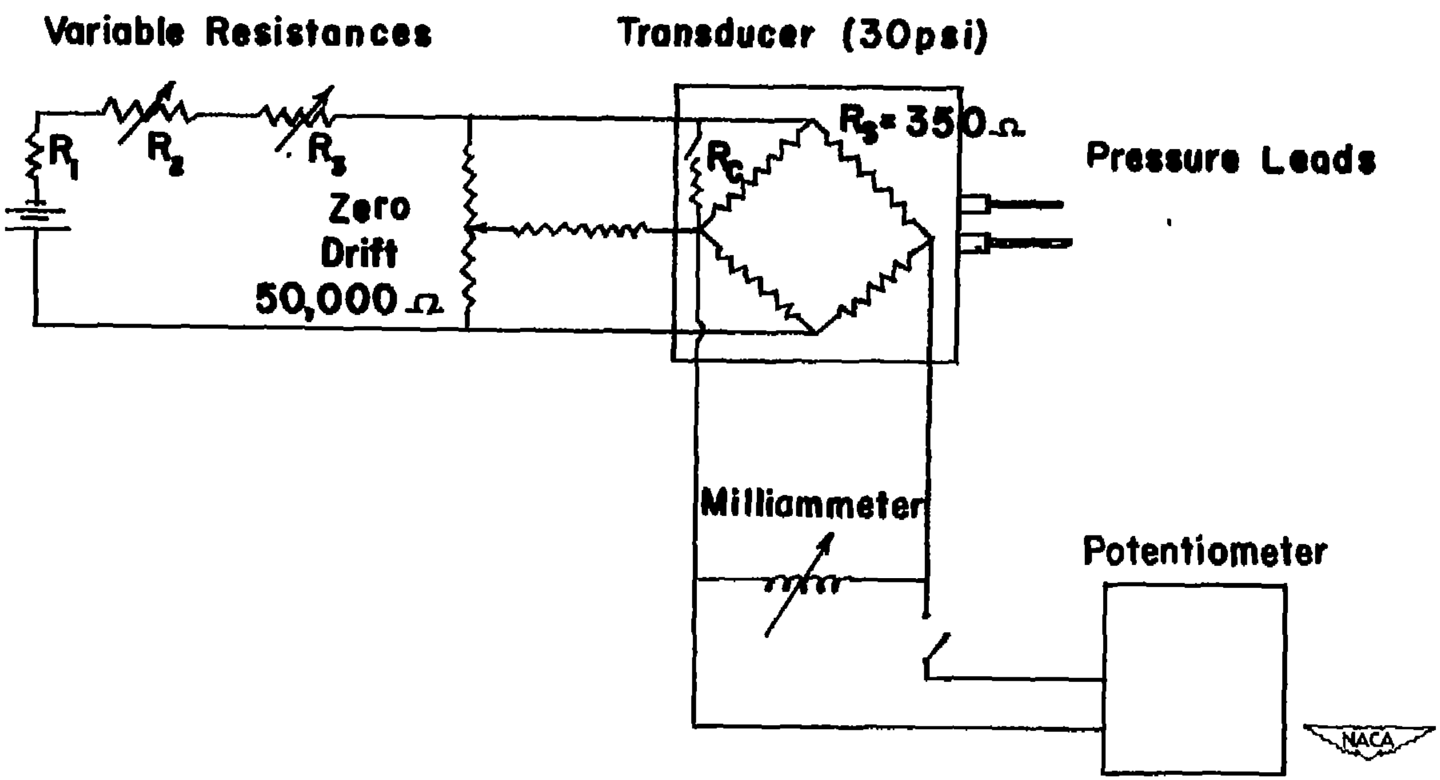

Figure 15.- Differential pressure drop across orifice plate.

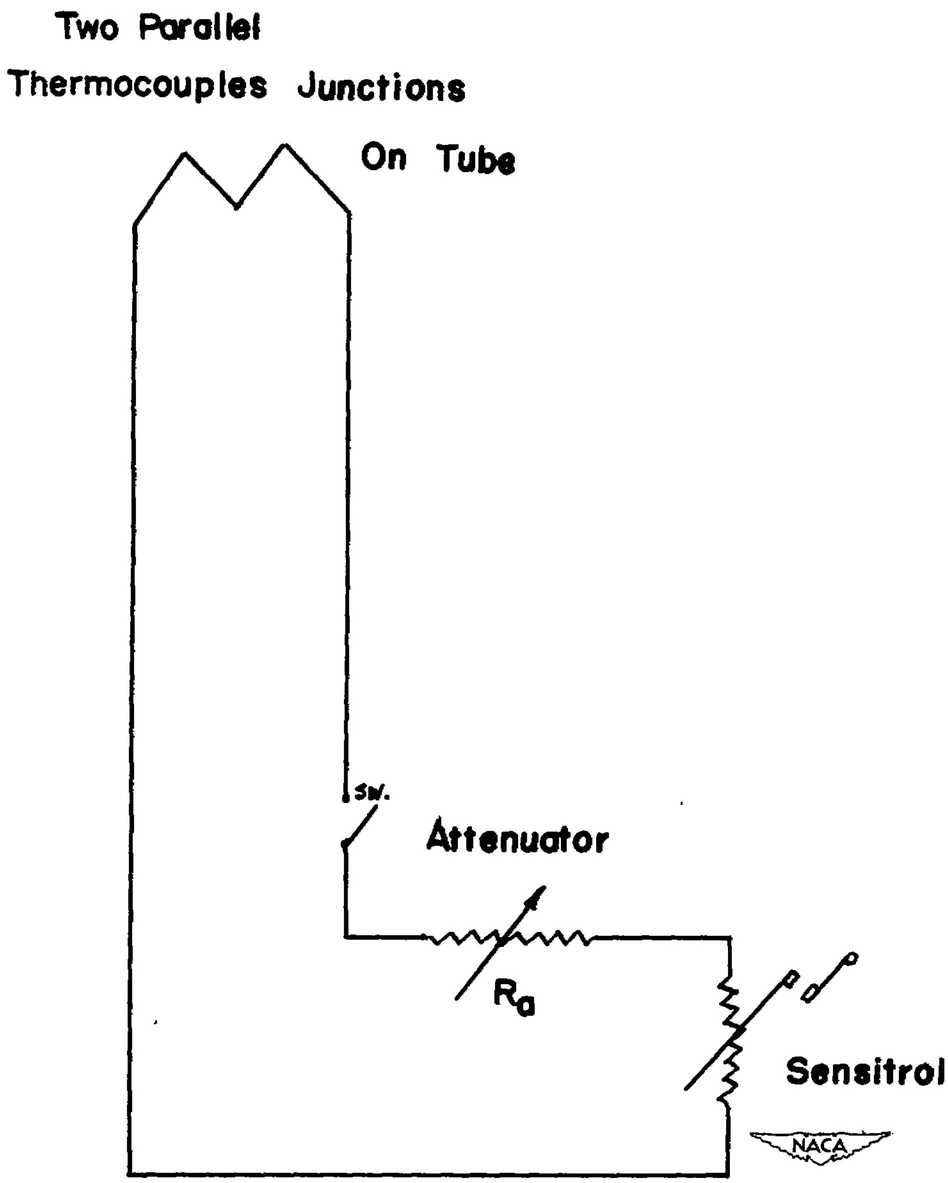

Figure 16.- Tube temperature safety control.

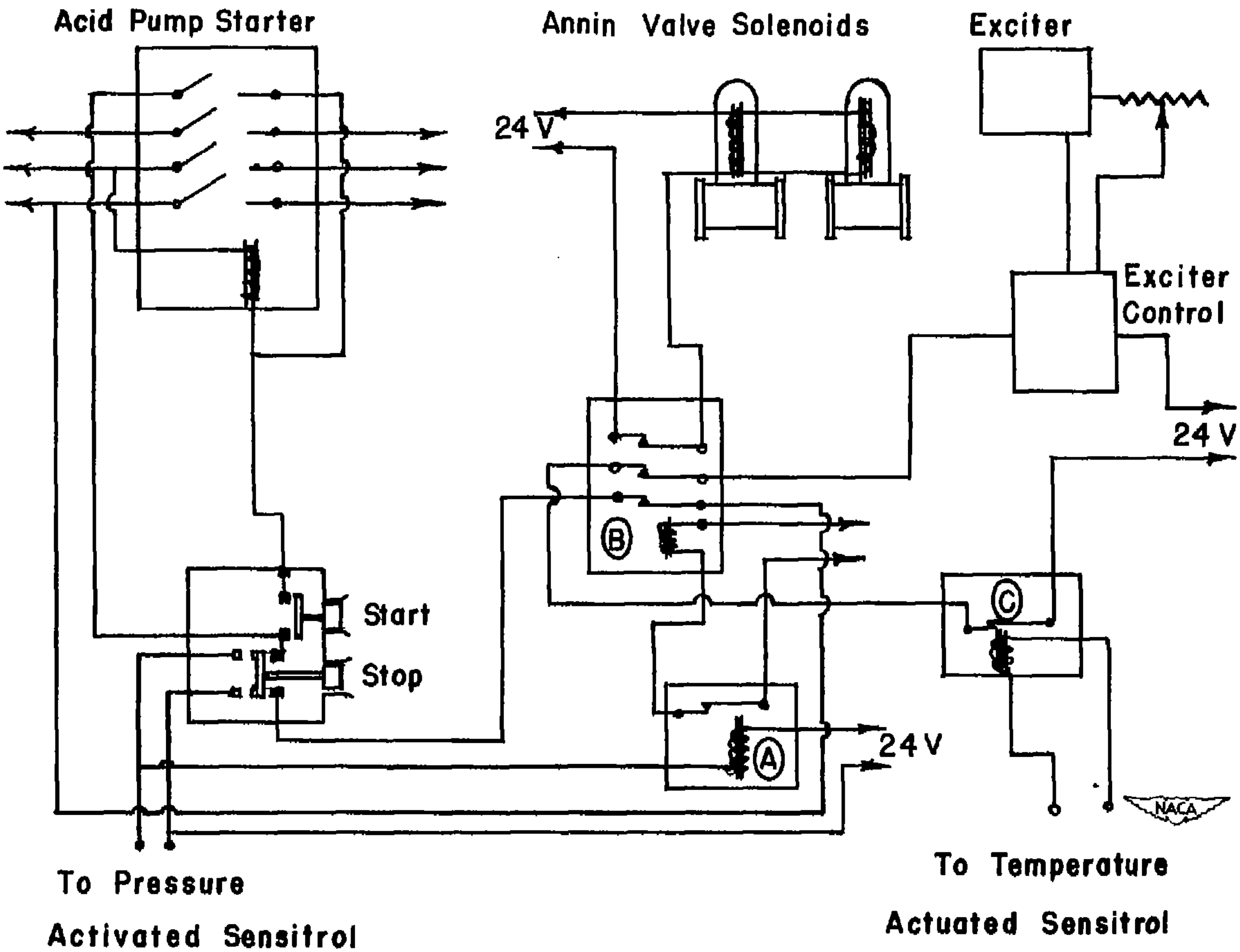

Figure 17.- Relay safety control circuits.